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Construction Engineering
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Canola Oil Fuel Cell Demonstration

Volume III – Technical, Commercialization, and Application Issues Associated with Harvested Biomass

John Adams, Craig Cassarino, Joel Lindstrom, Linda Eslin,
Scott M. Lux, and Franklin H. Holcomb

August 2006

Bio-based materials, such as vegetable oils, represent an available and renewable source of hydrogen for fuels.

Photo by Dr. Brent Bean, Texas Cooperative Extension

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Scott M Lux and Franklin H. Holcomb
Construction Engineering Research Laboratory (CERL)
U.S. Army Engineer Research and Development Center
2902 Newmark Dr.
Champaign, IL 61824

Linda Eslin
Concurrent Technologies Corporation (CTC)
100 CTC Road
Johnstown, PA 15904

John Adams[(1)], Craig Cassarino[(2)], and Joel Lindstrom[(3)]
Leonardo Technologies, Inc. (LTI)
70245 Bannock Uniontown Road
PO Box 178
Bannock, OH 43972-0178
(1) Mr. Adams works from LTI's Murrysville, PA Offices.
(2) Mr. Cassarino works from LTI's Bedford, NH Offices.
(3) Mr. Lindstrom works from LTI's Bozeman, MT Offices.

Final ReportFinal Report

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Abstract: This study evaluated the use of Montana-based oilseed crops (canola oil) for power generation in defense and civilian fuel-cell applications. Three major fuel production operations were considered: (1) recovery of oil from the harvested vegetable crop, (2) conversion of the vegetable oil into its biodiesel corollary, and (3) reforming the biodiesel into a synthesis gas. The study explored areas for potential improvements in the cost or technical performance in these major operations. Various commercialization pathways for agriculturally derived fuels were evaluated, with an emphasis on dual use opportunities. This work identified potential commercial and military applications for small, remote power generation systems, including fuel cells, which operate using those agriculturally derived fuels. This report documents barriers to commercialization that must be overcome, potential resolutions to those barriers, and stimuli for commercialization that can effectively advance the interests of key Department of Defense and Montana stakeholders in using Montana-based vegetable oil crops for remote power generation.

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Preface

This study was conducted under Work Unit CFE-B033, "Canola Oil Fuel Cells." The technical monitor was Robert Boyd, Office of the Director, Defense, Research, and Engineering (ODDR&E).

This research was performed by the Energy Branch (CF-E), of the Facilities Division (CF), Construction Engineering Research Laboratory (CERL). The CERL Principal Investigators were Scott M. Lux and Franklin H. Holcomb. Project management was provided by Concurrent Technologies Corporation (CTC) under Contract No. DACA42-02-2-0001. The Technical Project Manager was Linda Eslin. Technical work was performed by Leonardo Technologies, Inc. under Contract No. DACA42-02-2-0001, Subcontract 040900114. John Adams, Craig Cassarino, and Joel Lindstrom are associated with Leonardo Technologies, Inc. Dr. Thomas Hartranft is Chief, CEERD-CF-E, and L. Michael Golish is Chief, CEERD-CF. The associated Technical Director was Dr. Paul Howdyshell, CEERD-CVT.

CERL is an element of the U.S. Army Engineer Research and Development Center (ERDC), U.S. Army Corps of Engineers. The Commander and Executive Director of ERDC is COL Richard B. Jenkins, and the Director of ERDC is Dr. James R. Houston.

Executive Summary

This study was conducted to assess the potential for using biodiesel derived from Montana-based oilseed crops as a fuel for power generating technologies, including fuel cells. The assessment was conducted and is reported in three parts:

1. Assessment of the economics of producing synthesis gas from vegetable oil
2. Identification of commercialization pathways for the increased production and use of biodiesel fuels
3. Evaluation of remote power generation system applications.

A major impetus for this work is to advance the potential for use of alternative renewable fuels available for stationary power generation in both defense and civilian applications, to contribute to enhanced homeland security, to contribute to a diversified national energy portfolio, and to help increase market supply and demand of oilseed products from agricultural economies such as those in Montana. Of particular interest to defense applications are power generation alternatives for remote, severe climate, and/or high elevation environments.

Vegetable oils are an underutilized renewable source of energy that can be produced from several different “cool weather” oilseed crops in Montana, including the canola, crambe, rapeseed, mustard, safflower, sunflower, and camelina varieties. Biodiesel fuels produced from these vegetable oils have been demonstrated as a suitable fuel in compression ignition engines. The production of synthesis gas, a hydrogen-rich gas produced through the reforming of organic materials, from vegetable oils or their biodiesel corollaries, are of interest for use with power generation technology systems including fuel cells, turbines and micro-turbines, combustion engines, boilers, etc. Synthesis gas can be used in virtually any technology where natural gas or propane is currently used as a fuel.

Vegetable oil and biodiesel production is well established and the economics are well documented. Economics have generally dictated the extent of use of these materials in industrial applications. The deployment of these materials for power generation applications is less widespread and neither the effectiveness of the power generation technologies nor the economies of those technologies is well demonstrated or documented. This is particu-

larly true for the reforming of vegetable oil or their biodiesel corollaries into a hydrogen-rich synthesis gas.

This study concludes that:

- Oilseed harvesting and biodiesel production processes are well defined.
- Power generation applications for biodiesel are not well defined (especially those requiring reforming technologies, e.g., fuel cells) and require substantial near-term laboratory research and development.
- Field demonstrations of power generation technologies for biodiesel fuels using reforming technologies should be deferred in lieu of the necessary laboratory research and development.
- Commercial applications of biodiesel fuels for power generation can be accelerated through incentives directed toward power generation applications rather than biodiesel production.

This study found that the technology maturity for oil extraction and conversion of the extracted vegetable oil into biodiesel is high. Conversely, the state of technology maturity for reforming technologies applied to vegetable oils or their biodiesel corollaries is low. The potential improvement in economic performance is highest for reforming technologies due mostly to the early stage of technology maturity (Table ES1).

Table ES1. Potential improvement in economic performance for reforming technologies

Process Step	Technology Maturity	Potential for Economic Improvement
Oil Extraction	High	Moderate
Conversion to Biodiesel	High	Low
Reforming to Syngas	Low	High

The technology issues associated with vegetable oil and biodiesel reforming need to be more fully explored and understood. This would be most effectively achieved with an emphasis on short-term investigations on reformer technology rather than on field demonstrations. Investigations should focus on reformer technologies suitable for application with agricultural crops, and on power generation technologies, e.g., fuel cell, microturbine, combustion engines, etc., that could use the produced syngas. This would advance applications to benefit deployed military units by enabling them to use agricultural crops (such as those already grown in Montana) and vegetation as fuel sources for power generation.

Overall, the economics of converting vegetable oils to a hydrogen-rich synthesis gas is dominated by the capital costs for the various reforming tech-

nologies. To advance the use of biodiesel fuels derived from oilseed crops in power generation applications, this study recommends that:

- Further research and development programs should be conducted to explore critical technical issues associated with reforming vegetable oils (such as those grown in Montana) and/or biodiesels into hydrogen-rich synthesis gas
- Short-term research efforts should emphasize investigations of reformer technologies, to be followed by field demonstration initiatives of power generation technologies requiring those reforming technologies.
- Demonstrations of power generation technologies (not requiring reforming technologies) should be conducted at Department of Defense (DOD), other Government, and private sector facilities to better define market applications and characteristics, to stimulate biodiesel production for those power generation applications, and to provide incentives for the use of biodiesel fuels in power generation applications.

Unit Conversion Factors

Multiply	By	To Obtain
acres	4,046.873	square meters
cubic feet	0.02831685	cubic meters
cubic inches	0.00001638706	cubic meters
degrees (angle)	0.01745329	radians
degrees Fahrenheit	(5/9) x (°F – 32)	degrees Celsius
degrees Fahrenheit	(5/9) x (°F – 32) + 273.15.	kelvins
feet	0.3048	meters
gallons (U.S. liquid)	0.003785412	cubic meters
horsepower (550 ft-lb force per second)	745.6999	watts
Inches	0.0254	meters
kips per square foot	47.88026	kilopascals
kips per square inch	6.894757	megapascals
miles (U.S. statute)	1.609347	kilometers
pounds (force)	4.448222	newtons
pounds (force) per square inch	0.006894757	megapascals
pounds (mass)	0.4535924	kilograms
square feet	0.09290304	square meters
square miles	2,589,998	square meters
tons (force)	8,896.443	newtons
tons (2,000 pounds, mass)	907.1847	kilograms
yards	0.9144	meters

1 Introduction

Background

Agriculture is the largest industry in the state of Montana, representing approximately 3.8 percent of its gross state product. Approximately 8.7 percent of the state's work force is employed in agriculture, which uses 64 percent of Montana's land area. Current regional and national interest in the production and use of renewable fuels for power generation applications suggests that Montana's agriculture industry could be well positioned to participate in an emerging market opportunity important to both national defense and homeland security.

Montana presents a number of unique challenges for defense and civilian power generation applications; the state is small, remote, resides at a high altitude, and has a cold climate. Overcoming the technical challenges posed by these characteristics merits consideration not only for defense and civilian power generation in Montana, but also for corollary applications in other locations throughout the United States and around the world.

Bio-based materials such as vegetable oils represent an available and renewable source of hydrogen that—if efficiently recovered—could serve as an important fuel source for small, specialty applications such as remote power generation using micro-turbine, fuel cell, and other technologies. The Engineer Research and Development Center, Construction Engineering Research Laboratory (ERDC-CERL) has been involved in demonstrating the use of these materials, especially canola oil, for power generation applications, including fuel cells. Bio-based fuels have the potential to advance the use of alternative fuels available for stationary power generation in both defense and civilian applications, to contribute to enhanced homeland security, to contribute to a diversified national energy portfolio, and to help increase market supply and demand of oilseed products from agricultural economies such as those in Montana.

Various agricultural communities, like those in Montana, have an economic interest in producing crops that have new market potential. Moreover, these communities are increasingly sensitive to the need to reduce

the energy cost component of their overall farm operation. By producing crops that could ultimately be used for power generation, agricultural communities can move toward energy self-sufficiency and sustainability. The production of vegetable oil crops with high hydrogen content represents one such new market potential for agricultural communities like those in Montana. Furthermore, these materials provide the opportunity for remote farm power generation needs to be satisfied by the harvested crop in conjunction with small power generation technologies such as fuel cells and micro-turbines.

Canola is a valuable agricultural crop produced in Montana that yields a characteristically “highly saturated” oil (i.e., oil with a high hydrogen content), which, if effectively recovered, could serve as a valuable fuel for small, remote power generation applications. Other Montana-based crops of interest include crambe, rapeseed, mustard, safflower, sunflower, and (more recently) camelina. Adams (2006) previously collaborated to evaluate these different agricultural crops as potential power generation fuel sources. Highly saturated vegetable oils include those derived from canola, crambe, and mustard. Less saturated (i.e., lower hydrogen content) vegetable oils are those derived from flax, safflower, soybean, and sunflower. Agricultural geneticists are developing hybrid crops that may yield higher oil and higher hydrogen content from all of these crops.

Vegetable oils represent potentially valuable sources of hydrogen for small, niche power generation applications that use technologies such as fuel cells, generator sets, micro-turbines, etc. Frequently, vegetable oil needs to be converted to its biodiesel corollary for power generation applications. Combining alcohols and vegetable oils under heat, pressure and a catalyst, can generate two products: (1) methyl or ethyl esters (long chain polymers of fatty acids and alcohols) and (2) glycerin or glycerol. The esters are simple long chain molecules known as biodiesels. Typically the alcohol used for the conversion of vegetable oils to biodiesels is either methanol or ethanol. When ethanol is used, the resulting biodiesel can be a highly renewable product. Biodiesels typically have less complex molecular structures than their originating oils, which in general makes them more efficient for use in power generation applications.

In addition, gases containing high concentrations of hydrogen are desirable for power generation applications. The conversion of the hydrocar-

bons in vegetable oils or their biodiesel corollaries to a hydrogen-rich gas stream (frequently referred to as a synthesis gas or "syngas") is done using fuel reforming technologies. The remaining components in reformed fuel streams are designed to be either carbon monoxide or carbon dioxide, depending on the reformer type employed. Fuel reformation can occur independently at temperatures around 1,400 °C or a catalyst can be used to lower the reaction temperature to 500 °C – 800 °C. This reduces the size of the reformer and helps achieve better control of the reformer reaction kinetics. Several different types of reforming technologies exist including autothermal, partial oxidation, plasma, steam, and thermal decomposition. These technologies can be used to convert a liquid feed stock into the high hydrogen content syngas.

This work follows two previous ERDC-CERL studies. *Canola Oil Fuel Cell Demonstration: Volume I – Literature Review of Current Reformer Technologies* (Adams 2004) evaluated methods to convert canola oil into a H_2-rich stream. Different reformer technologies were rated for their potential to reform canola oil or canola biodiesel into a high quality syngas for use in fuel cell applications. Based on an evaluation using feasibility, applicability, availability, and cost criteria, catalytic partial oxidation (CPOX) reformer was reported to be the potentially most applicable technology for canola oil or canola biodiesel reforming in fuel cell applications. *Canola Oil Fuel Cell Demonstration: Volume II—Market Availability of Agricultural Crops for Fuel Cell Applications* (Adams 2006) identified various Montana oil crops available for reforming as a feedstock fuel in fuel cell applications, and found that the use of vegetable oils (or vegetable oil-derived bio-fuels) in Montana alone could potentially sustain more than 6000 fuel cell units, 5.0 kW in size.

The reformation of vegetable oil crops for power generation applications, including fuel cells, is not well known. While these sustainable fuel resources represent a viable alternative and complement to traditional petroleum-based fuels, there is a clear need for substantial work in the area of reformer technologies with vegetable oils and their biodiesel corollaries prior to field demonstration of fuel cells, or other power generation technologies, using these materials. This study was undertaken to investigate appropriate short-term technical initiatives to most effectively advance the interests of key Department of Defense (DOD) and Montana stakeholders in using Montana-based vegetable oil crops for remote power generation.

Objectives

This study builds on prior work coordinated with Leonardo Technologies, Inc. and Montana State University (MSU). The overall goal of that project was to demonstrate a year-long operation of a Proton Exchange Membrane (PEM) fuel cell in Yellowstone National Park using canola oil feedstock. Results of this prior study showed that recent activities in reforming technology were unsuccessful. The objectives of this work were to:

1. Evaluate the economics of producing vegetable oil-based fuels
2. Investigate various commercialization pathways to spur the development of vegetable oil-based fuels
3. Identify pertinent power generation applications for the oilseed-derived fuel products.

Approach

This work was conducted in three parallel parts:

1. An economic evaluation of producing vegetable oil-based biodiesel fuels (to study the production of synthesis gas from reforming vegetable oil-derived biodiesel fuels for power generation applications)
2. An investigation of the commercialization pathways to increase market growth of biodiesel
3. A study of various power generation applications using biodiesel fuels (t0 study defense and civilian remote power generation applications that may have use for bio-based fuels).

Literature reviews and evaluations of various technology alternatives were conducted to document the processes and equipment necessary to produce synthesis gas from biodiesel fuels. Commercial equipment suppliers and users were interviewed to gain further understanding of current business models, as well as to learn of issues that inhibit increased deployment of process technologies. Ultimately, information was gathered to assess potential commercialization pathways for increased production and sale of existing or new products. Interviews with researchers at universities and private organizations were conducted to gather data as well as to shed light on current development initiatives. The findings were compiled and recommendations were formulated to provide a framework that could advance the application of bio-based fuels derived from Montana oilseed crops for use in defense and civilian power generation applications.

Mode of Technology Transfer

This report will be made accessible through the World Wide Web (WWW) at URLs:

http://www.cecer.army.mil

http://dodfuelcell.cecer.army.mil/lib_resources.php4

2 Biomass Study

The technical process of fueling fuel cell systems with vegetable oil-based products follows these steps (shown in Figure 1):

1. Harvest canola, crambe, mustard, rapeseed, safflower, and sunflower oilseeds.
2. Extract oil from the oilseed crops.
3. Convert the oils into methyl or ethyl esters (biodiesels).
4. Reform the vegetable oils or biodiesels to high hydrogen content synthesis gas (i.e., “syngas”).
5. Use the syngas for power generation.

Seed Delivery / Storage
↳ **Crushing / Oil Extraction**
↳ **Conversion to Biodiesel**
↳ **Reforming to Synthesis Gas**
↳ ↳ **Synthesis Gas Used for Power Generation**

Figure 1. Process of fueling fuel cell systems with vegetable oil-based products.

This chapter examines three of these important process steps: (1) the extraction of the oil from the seed crop, (2) the conversion of that oil to its biodiesel corollary, and (3) the reforming of that biodiesel into a hydrogen rich synthesis gas (or syngas). The unit processes within each of these steps contribute to the overall economics of using fuels derived from agricultural products grown in Montana. This results of this analysis will help clarify how bio-based fuels derived from Montana agricultural crops can successfully be made commercially available for use in fuel cell, microturbine, and other power generation technologies in both defense and civilian applications. This effort will also help to identify and prioritize process areas that need further research and development to increase the overall commercial viability of these bio-based fuels.

Based on interviews conducted for this study, Montana farmers report that because there is currently a low market demand for biodiesel, there is little motivation to grow oil seed crops such as canola for that purpose (Daniel

2005). The cost of biodiesel production is currently a major barrier to its widespread deployment as a combustible fuel for use in compression ignition (diesel) engines. In addition, the reformation of vegetable oil or biodiesel feedstock (i.e., the conversion of the oil or biodiesel into syngas) is also expensive. However, reforming may allow a greater number of power technology options to be considered to overcome current barriers and stimulate an accelerated commercialization of Montana agricultural crops as a power generation fuel source. Vegetable oils and their biodiesel corollaries represent potentially viable feedstock for syngas production for various power generation technologies including fuel cells and micro-turbines. Alternative commercialization pathways are addressed in a later section of this report.

Oil Extraction

Adams (2006) identified six Montana agriculture crops as having good potential for biodiesel and synthesis gas production:

- canola (*Brassica napus* or *B. rapa*)
- crambe (*Crambe abysinica*)
- mustard (*Brassica juncea*)
- rapeseed (*Brassica napus*)
- safflower (*Carthamus tinctorus*)
- sunflower (*Heliothus annus*).

More recently, researchers at Montana State University report the development of a new crop, camelina sativa (also known as false flax or gold of pleasure), that presents good potential as well (Pilgeram 2005). These crops are important to the agriculture industry of Montana and represent current feedstock resources for remote power generation applications. Table 1 lists the characteristics of current oilseed production in Montana, including pertinent oilseed crop harvest statistics for canola, mustard, safflower, and sunflower. (Data was insufficient to include crambe and rapeseed in this listing.) Significant amounts of flax are also produced in Montana, but flax yields are generally too low to consider them as an energy crop. Although there have also been reports of experimental-size soybean plantings in Montana, soybeans do not do well in cool weather climates and are not considered a viable commercial Montana crop (Johnson 2005).

Table 1. Annual oilseed harvest statistics in Montana.

Oil Crop	Acreage (10^3 acres)		Seed Production		Crude Oil
	Planted	Harvested	Yield (lb/acre)	Total Yield (10^3 lb)	Yield (lb/acre)
Canola					
2004	15.0	15.0	1,590	23,850	620
2003	28.0	27.0	940	25,380	367
2002	37.5	34.5	860	29,670	335
2001	58.0	49.5	910	45,045	355
2000	65.0	58.0	960	55,680	374
1999	60.0	58.0	1,200	69,600	468
6-Year Average	*43.9*	*40.3*	*1,077*	*41,537*	*420*
Mustard					
2004	11.5	11.4	700	7,980	224
2003	20.5	20.2	610	12,322	195
2002	27.0	25.0	440	11,000	141
2001	11.0	10.0	850	8,500	272
2000	12.0	10.0	700	7,000	224
1999	21.5	21.0	850	17,850	272
6-Year Average	*17.3*	*16.3*	*692*	*10,775*	*221*
Safflower					
2004	33.5	31.0	680	21,080	231
2003	42.5	42.0	770	32,340	262
2002	39.5	38.0	800	30,400	272
2001	31.0	28.0	850	23,800	289
2000	41.5	39.0	770	30,030	262
1999	41.0	39.0	850	33,150	289
6-Year Average	*38.2*	*36.2*	*787*	*28,447*	*268*
Sunflower					
2004	5.0	4.5	975	4,388	410
2003	2.6	1.2	763	915	320
2002	1.7	1.6	580	928	244
2001	2.5	2.0	370	740	155
2000	5.5	4.1	741	3,039	311
1999	7.8	7.1	860	6,095	361
6-Year Average	*4.2*	*3.4*	*715*	*2,684*	*300*

Source: U.S. Department of Agriculture (USDA) (2006).
Note: Total Yield of Seed Production includes hulls.

Note that the yields listed in Table 1 are much lower than long term averages for each crop due to recent drought conditions that have been experienced in Montana. For example, the 6-year average for the canola harvests listed in Table 1 is calculated to be 1,077 lb/acre, but long term averages for canola are approximately 1,667 lb/acre (Johnson 2005). Figure 2 shows the 6-year averages of each of these oilseed plants.

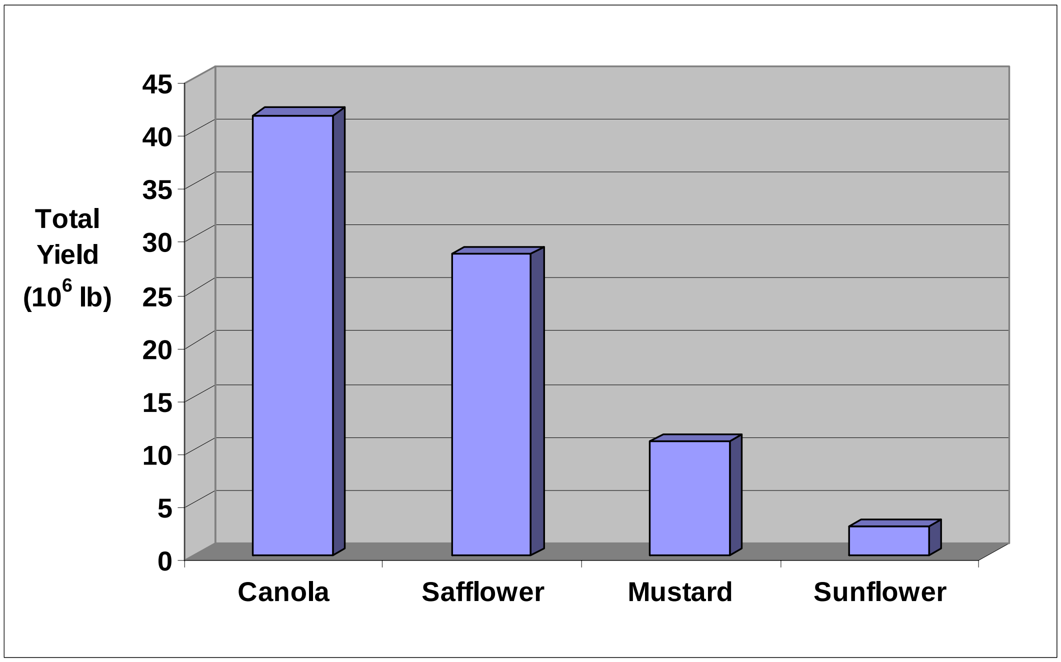


Figure 2. Average seed production in Montana from 1999–2004.

In their native state, vegetable oils extracted from oilseeds exist primarily as triglycerides (three fatty acids, R_1, R_2 and R_3 (Figure 3), bonded to a molecule of glycerin). For the purposes of this study, all vegetable oils are assumed to be produced as triglycerides.

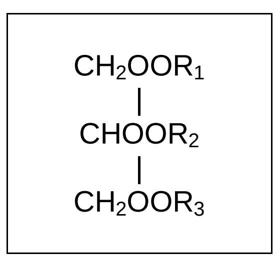


Figure 3. A triglyceride (vegetable oil) molecule.

The oil from these seed crops can be recovered in two distinctly different ways, either by seed crushing with or without solvent extraction.

Oil Recovery from Seed Crushing With Solvent Extraction

Oil extraction using solvents is a combination of mechanical pressing with solvent extraction. The use of solvents aids in the extraction and recovery of the seed oil. One popular solvent is hexane, but other solvents, such as alcohol or carbon dioxide, may be used. There is an added level of complexity to this process alternative because of the associated fire, explosion and environmental issues introduced by the solvent. Efforts to recover and reuse the solvent add additional cost.

Processing temperatures used in solvent extraction processing are typically lower than with mechanical pressing alone. Oil yield using solvent extraction is typically 35 to 40 percent by weight (i.e., 35 to 40 lb of oil for each 100 lb of seed) (Turnbull 2005). The processes for oil extraction and recovery when using a solvent (adapted from the Canola Oil Council [2005] and Kadharmestan et al. [1997]) can be summarized as:

- *Seed Cleaning* is usually conducted in three steps in a single mechanical unit: (1) aspiration, (2) screen separation to remove oversized particles, and (3) screen separation to remove undersized particles. Moisture content of the seed is also monitored and should be maintained between 6 and 10 percent for optimal operation.
- *Seed Preconditioning* preheats the whole seed to approximately 30 to 40 °C in a grain dryer to prevent the shattering that may occur when cold seed from storage enters the flaking unit (Unger 1990). This technique also improves flaking, screw pressing capacity, cake formation, extractability, and hexane recovery from the extracted seed flakes.
- *Flaking* through the use of roller mills helps to rupture the cell walls of the seed to allow the seed oil to be extracted. The liquid oil migrates to the outer surface of the flake, where it is separated. Flaking also allows the solvent to penetrate into the cellular structure, dissolving and diluting the seed oils. Flaking is typically done between two smooth surface cast-iron rolls. The thickness of the flake is important, with an optimum of between 0.3 to 0.38 mm. Flakes thinner than 0.2 mm are very fragile while flakes thicker than 0.4 mm result in lower oil yield.
- *Cooking* is conducted by passing the flakes through a series of steam-heated drum or stack-type cookers. Cooking serves to thermally rupture oil cells that have survived flaking; to reduce oil viscosity and thereby promote coalescing of oil droplets; to increase the diffusion rate of prepared oil cake; and to denature hydrolytic enzymes. Cooking

also adjusts the moisture of the flakes, which is important in the success of subsequent pre-pressing operations. At the start of cooking, the temperature is rapidly increased to 80-90 °C. The rapid heating serves to inactivate enzymes that could produce undesirable breakdown products that affect both oil and meal quality. The cooking cycle usually lasts 15 to 20 minutes and the temperatures usually range between 80 and 105 °C, with an optimum temperature of about 88 °C. Higher cooking temperatures can volatize some sulfur compounds that can cause odors in the oil. However, these high temperatures can negatively affect meal protein quality.

- *Pressing* often occurs in a series of low pressure continuous screw presses or expellers. These units consist of a rotating screw shaft within a cylindrical barrel. The rotating shaft presses the cake against an adjustable choke, which partially constricts the discharge of the cake from the end of the barrel. This action removes most of the oil while avoiding excessive pressure and temperature. The objective of pressing is to remove as much oil from the seed as possible, usually between 60 and 70 percent, while maximizing the output of the expellers and the solvent extractor, and the quality of presscake.
- *Solvent Extraction* is often used subsequent to the screw press to remove the remaining oil from the press cake, since pressing alone is not able to remove all of the oil. The cake from the expellers, which contain between 14 and 20 percent oil, are sometimes broken into uniform pieces prior to solvent extraction. In solvent extraction, hexane specially refined for use in the vegetable oil industry is used. Various mechanical designs of solvent extractors have been developed for moving the cake and the miscella (solvent plus oil) in opposite directions to effect a continuous counter current extraction. Basket and continuous loop type extractors are commonly used for canola. The principles of operation for each type of solvent extraction technology are the same; cake is deposited in the extractor, which is then flooded with solvent or miscella. A series of pumps spray the miscella over the press cake with each stage using a successively “leaner” miscella, thereby containing a higher ratio of solvent in proportion to the oil. The solvent percolates by gravity through the cake bed, diffusing into and saturating the cake fragments. The hexane-saturated meal that leaves the solvent extractor, after a fresh solvent wash, contains less than 1 percent oil.
- *Desolventizing* is the step where solvent is removed from the saturated meal. In a series of compartments or kettles within the desolventizer,

the majority of the solvent is flashed from the meal by the injection of steam. The final stripping and drying of the meal is accomplished in the subsequent compartments heated to between 103 and 107 °C. The total time spent in the desolventizer is approximately 20 minutes. The meal emerges free of solvent and contains about 1 percent residual oil and 15 to 18 percent moisture. After drying to 8 to 10 percent moisture and cooling, the meal is typically granulated to a uniform consistency and then either pelleted or sent directly as a mash to storage.

- *Distillation* of the solvent from the oil allows for solvent recovery and reuse.
- *Degumming* is conducted on the resulting oil to remove gums and free moisture prior to oil storage.

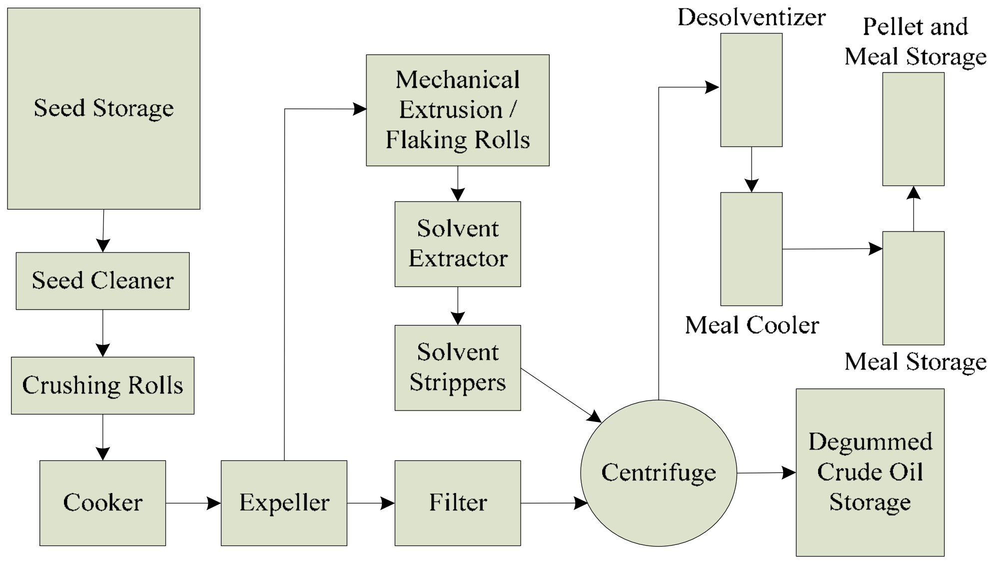
Figure 4 shows the process.

Oil Recovery from Seed Crushing Without Solvent Extraction

Typically referred to as "cold pressing," this non-solvent alternative for oil recovery is essentially the same as the solvent process—except that the solvent and all solvent related operations are eliminated. In "cold pressing," the primary means of oil extraction and recovery is through mechanical pressing. Temperature control at (or about) 60 °C throughout this mechanical process is more important than with solvent extraction, though oil recovery is improved at higher temperatures. Typical oil recovery from cold pressing is 33 percent by weight (i.e., 33 lb of oil for each 100 lb of seed). Figure 5 shows the cold pressing process for oil extraction.

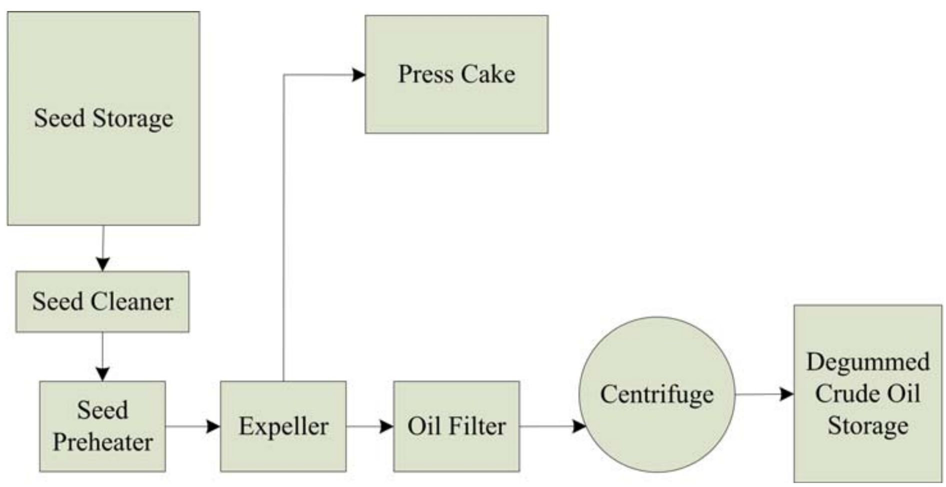
Seed cleaning removes any foreign debris from the seed including stones, metal, and undesired plant material to a contamination level of below 2 percent to reduce risk of damage to the press. A sieve is used to remove stones and plant parts, and a magnetic separator is often used to remove metals.

Seed preconditioning preheats the seed to room temperature, or 20 °C, often from excess heat derived from the press cake. There is no benefit to heating the seed above 20 °C.



Source: Canola Oil Council (2005)

Figure 4. Prepress solvent extraction process.



Source: Ferchau (2000)

Figure 5. Flow diagram of a cold press extraction process.

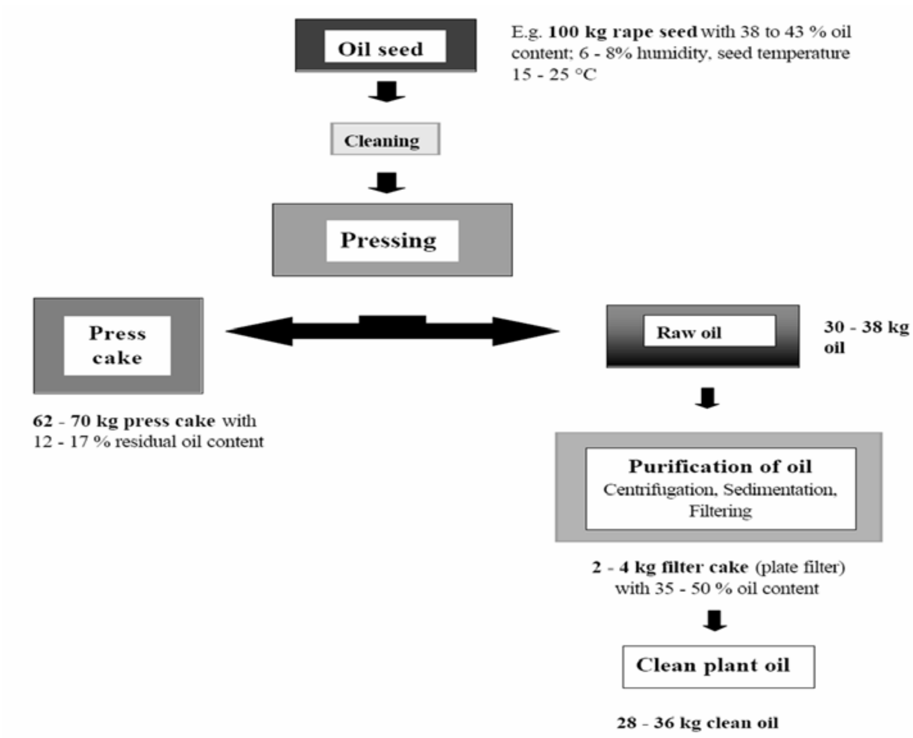
Cold Pressing is defined as a mechanical press operation that takes place at or below 50 °C. Though, not all mechanical press operations can be classified as a cold press, since they do not stay below this temperature (Phillips 2005). In some cases, it is necessary to heat the press cake outlet to avoid blockage of this part of the press. This heating is generally in the range of 60 to 80 °C, which results in an oil temperature increase that can approach 40 °C. Cooling the press cake is required prior to storage.

Degumming in the cold press extraction process is much the same as that in the solvent extraction process.

Figure 6 shows typical cake and oil yield characteristics. The prepress cake represents 62 to 70 percent of the input seed weight when crushed in a cold press extraction system. The remaining mass of the input seed is recovered in the form of raw oil. This oil subsequently undergoes filtering and degumming processes, which ultimately reduces the final quantity of oil to approximately 28 to 36 percent of the input seed weight (Ferchau 2000).

Cost Overview

Table 2 lists capital and operating costs for solvent and mechanical extraction.



Source: Ferchau (2000)

Figure 6. Typical cold press yield characteristics.

Table 2. Cost overview for oil recovery from seed crop.

	Solvent Extraction			Mechanical Extraction		
Plant size (MGY)	5	10	15	3	5	10
Total capital cost ($Million)	N/A	14.2 – 16.4	21.4 – 24.5	5.6	7.3	10.6
Operating costs ($/gal oil)	N/A	0.44	0.44	N/A	N/A	N/A

Source: Duff (2004), English et al. (2003)

Note: This data includes degumming; does not include glycerin distillation capital costs; includes owners cost (inventory, land, buildings, organizational, etc.); and assumes approximately 330 days per year operation. Operating cost does not include feedstock and does assume continuous operation.

It has been reported that oilseed crushing plants with a capacity above 10 million gal of oil per year generally use solvent extraction systems. In contrast, oilseed crushing plants with a capacity below about 5 million gal of oil per year generally employ only mechanical extraction equipment.

Oil extraction is a mature process with only small incremental improvements anticipated in process efficiencies and cost. A greater potential is the development of low input / high yield crops—such as Montana State University's work with camelina—that could reduce the overall cost of oil. In addition, crop development could provide further enhancements to the oil quality including higher hydrogen yield and lower content of undesirable constituents such as sulfur and phosphorus.

Crop Production Characteristics

Adams (2006) reported that the theoretical oil production from both optimum and limited production lands is more than 298 million lb with an associated theoretical hydrogen production of more than 33 million lb (Table 3). Maximum production represents maximum input including Class I lands, high rainfall or irrigation, and optimum frost-free period. Class II lands involve production on lands of low productivity (lower fertility, salt, or low rainfall). Oilseed crops will be competing for Class I lands with other crops. Class II lands are less competitive and more likely to be used for oilseed production.

Table 3. Oil/hydrogen production using Class I and Class II land in Montana.

Crop	Acres Planted	Seed Yield (lbs/acre)	Seed Production (lbs)	% Oil Yield*	Oil Recovered (lbs)	% H_2 Yield**	Total H_2 Production (lbs)
Canola	110,000	1,200	132,000,000	0.39	51,480,000	0.11	5,662,800
Crambe	80,000	1,000	80,000,000	0.32	25,600,000	0.14	3,584,000
Mustard	400,000	1,000	400,000,000	0.32	128,000,000	0.10	12,800,000
Rapeseed	65,000	1,100	71,500,000	0.39	27,885,000	0.14	3,903,900
Safflower	100,000	1,200	120,000,000	0.34	40,800,000	0.12	4,896,000
Sunflower	65,000	900	58,500,000	0.42	24,570,000	0.10	2,457,000
Total per annum		862,000,000	298,335,000		33,303,700		

* % pounds of oil yield per pounds of seeds

** % pounds of H_2 yield per pounds of oil

Note: Land use assumptions above for No. I and No. II Classification (optimum and economically feasible production environments).

This study assumed that 100 percent of the hydrogen could be extracted from the vegetable oil. In most applications, however, a 70 to 80 percent assumed conversion efficiency would be more accurate. Data for potential production of oilseeds was derived by entering variables into an ARC/Info crop mapping system using Global Positioning Satellite (GPS) technology developed by Montana State University. This crop mapping system uses as many as 150 variables, each of which can be evaluated at a multitude of levels. An example variable would be "days of frost-free production." Each variable can be layered on top of the prior variable to create a crop map of all conditions defined. Figure 7 such a crop map for a canola oil crop. The map provides a defined area of high productivity. The grid units are defined as 2 by 3 miles in size with at least 50 percent of that area being highly adapted to canola production. Other variables include soil type, rainfall patterns, soil types, first and last frost, etc.

In many areas, crops such as canola, crambe, mustard, and rapeseed overlap in production requirements. Since no more than one fourth of the suitable land can be used annually for any one crop, crop rotation is considered essential. For example, in year one, an acre of land could be planted to canola. The following year the same acre could be planted to sunflower, followed by crambe and safflower. In the 5th year, the land would return to canola. This crop rotation would achieve maximum land use for fuel.

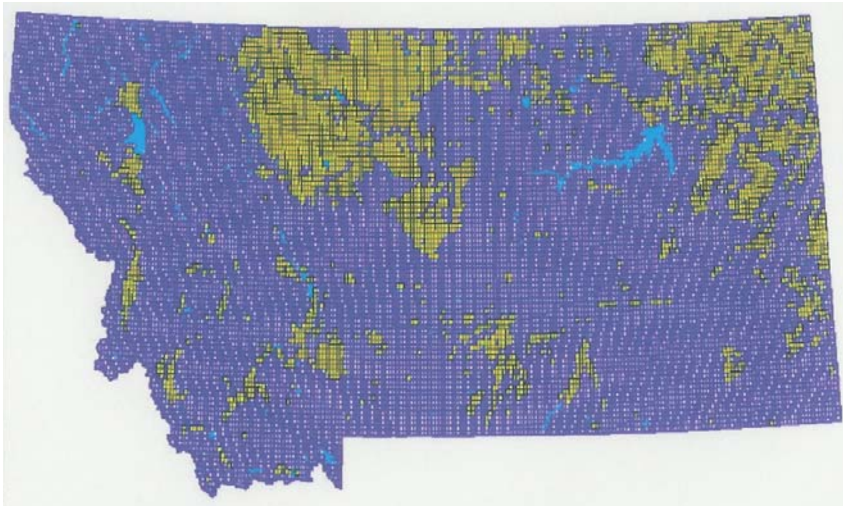


Figure 7. Class I Land available to plant canola crop annually in Montana.

As oils become more unsaturated (lacking hydrogen), yields of hydrogen will decrease. Polyunsaturated oils include flax, safflower, soybean, and sunflower. Higher oleic oils such as canola, crambe, and mustard have more saturated oils (more hydrogen) and will yield more hydrogen. However, high oleic versions of safflower, sunflower, and soon soybean, will be available as well.

Based on the presented results, seeds, oil, and hydrogen yields are nearly the same for the selected six oil crops (Table 4). Differences are due to saturation of the oil derived from each crop planted. Other changes could result from process efficiencies that would affect the yields oil recovery or hydrogen production at each stage of the production.

Table 4. Oil/hydrogen production per acre.

Crop	Oil Recovered (lbs/acre)	Total H_2 Production (lbs/acre)	H_2 Yield (lb H_2 / lb Oil)
Canola	468	51.5	0.11
Crambe	320	44.8	0.14
Mustard	320	32.0	0.10
Rapeseed	429	60.1	0.14
Safflower	408	49.0	0.12
Sunflower	378	37.8	0.10

Oil Characteristics

Table 5 lists pertinent chemical and physical properties of the six vegetable oils considered in this work. For comparison, the properties of soy oil are also included in this table. Of particular interest in Table 5 is the hydrogen and sulfur content of the various oils. High hydrogen concentration is desirable since, in principle, the resultant synthesis gas used as a fuel stream would have more hydrogen. Sulfur content is also a very important parameter since it could lead to the need for emission control systems on the power generation technologies and could be a poison, even at very low levels of concentration, to process catalysts used for environmental control, in reformer technologies, or in the power generation systems themselves such as fuel cells.

Sulfur occurs in vegetable oils naturally, although it is also possible to introduce it through other means, such as fertilization (Gannon 2005). Sulfur is present naturally in the form of organic compounds as the decomposition products of glucosinolates (Przybyiski 2000). Rapeseed and mustard were reported to be high in glucosinolates (high in sulfur), and conversely, canola and soybean were said to be low in glucosinolates (low in sulfur) (Peterson 2005). This sulfur content consideration alone makes the canola and soy oils more attractive than the rapeseed and mustard oil varieties. Sulfur content in vegetable oils is generally decreased as a result of degumming, refining, bleaching, and deodorization procedures. However, it is not known which vegetable oil-derived biodiesels will have sulfur content levels low enough to eliminate the need for sulfur removal equipment in fuel cell systems.

Catalysts in reformer systems are also known to experience deactivation due to sulfur poisoning. To minimize the impact of sulfur poisoning, the reformer can be run at higher temperatures (800–900 °C). However, achieving such high temperatures requires the use of significantly more energy input, often in the form of air (for partial oxidation processes) and steam (to prevent the formation of carbon). Increased steam is needed since the oxygen-to-carbon feed ratio and gas mixture temperature are dominant factors that control carbon formation. Thus, a substantial overall system efficiency penalty is generally sustained to extend reformer life when operating on fuels with high sulfur content.

Table 5. Properties of various degummed and refined vegetable oils.

	Canola	Rape	Sunflower	Crambe	Safflower	Soy
Composition						
Hydrogen (wt %)	10.7	12.2 – 12.4	11.5 – 12.3			11.5 – 12.4
Carbon (wt %)	80.2	76.1 – 76.5	75.6 – 77.7			76.2 – 77.4
Oxygen (wt %)	9.1	11.2 – 11.4	10.4 – 12.4			10.5 – 11.6
Sulfur (ppm)	3 – 15	5 – 220	2 – 10			2 – 10
Density (20 °C, lb/gal)	7.61 – 7.68	7.59 – 7.69	7.69 – 7.73		7.68 – 7.76	7.5 – 7.7
Viscosity (40 °C, cS)	33.5 – 37	37.0 – 51.3	30.6 – 37.1	53.6	31.3 – 32.7	28 – 36.8
Viscosity (20 °C, cS)	70 – 75		60 – 67.1			57 – 71.8
Cloud Point (°C)		(-3.9)	(-7.7) – 7.2	10	18.3	(-4) – (-1)
Pour Point (°C)		(-31.7)	(-15) – (-9)	(-12.2)	(-6.7)	(-12.2) – 9
Flash Point (°C)	275 – 290	246	232 – 323	274	260	219 – 330
Heating Value (BTU/lb)						
Gross (HHV)	17,240	16,896 – 17,756	16,939 – 17,068		16,939 – 16,982	15,993 – 17,584
Net (LHV)			15,821 – 15,907	17,412		15,821 – 15,950

Source: Adapted from Przybyiski (2000), De Winne (2004), Idem et al. (1997), Goering (1982), Ryan et al. (1982), Tahir et al. (1982), Auld et al. (1982), Collins et al. (1982) , Pischinger et al. (1982), Vinyard et al. (1982), Baranescu and Lusco (1982), Strayer et al. (1982) and Ziejewski and Kaufman (1982).

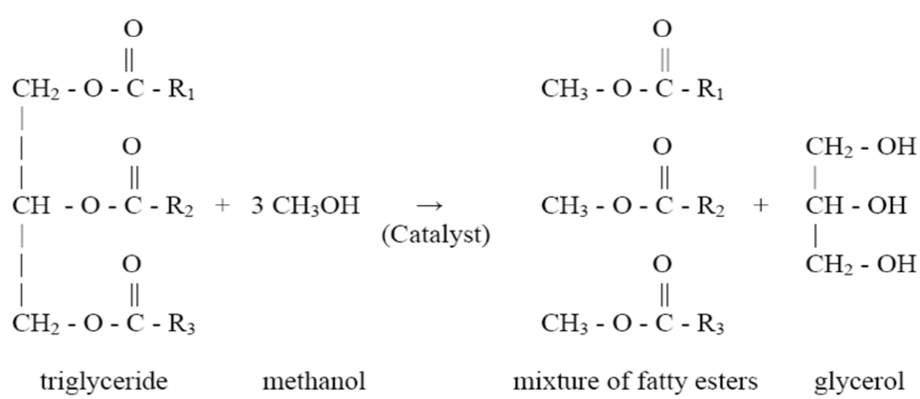
Note: There was insufficient data to include data for mustard oil.

For power generation applications such as fuel cells and turbines, low sulfur concentration may be as important as high hydrogen concentration. Sulfur removal equipment adds significant cost to power generation systems and generally require periodic maintenance (Arthur D. Little 2001). Thus, research spent on the development of vegetable oils with high hydrogen content and negligible sulfur content is warranted, since it may be possible to eliminate sulfur removal equipment entirely when operating power generation systems such as fuel cell and turbine systems on biodiesel fuels (Przybyiski 2000).

Vegetable Oil to Biodiesel Conversion

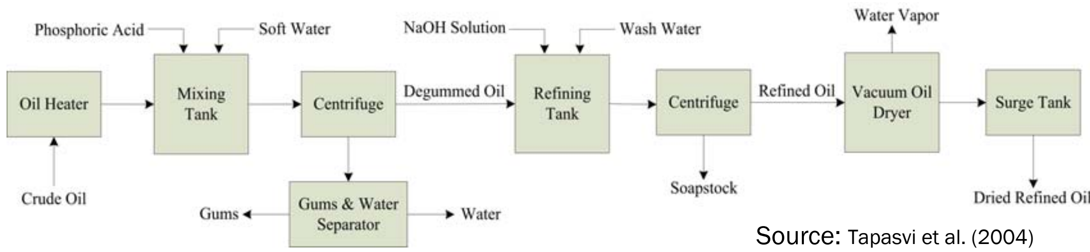
By combining alcohols and vegetable oils with a catalyst under heat and pressure, three products can be generated: (1) methyl or ethyl esters- long chain polymers of fatty acids and alcohols; (2) fatty acids; and (3) glycerin (or glycerol).

By producing esters, the vegetable oils (or triglycerides) become simple long chain molecules. These materials are known as biodiesels. Chemically, biodiesel is defined as the mono-alkyl esters of long-chain fatty acids derived from lipid sources (Tapasvi et al. 2004). The type of ester produced is determined by the alcohol used in manufacturing. Typically, methanol or ethanol is used (Figure 8). Methanol is typically derived from petroleum processing and is more toxic and hazardous to handle than ethanol. Ethanol can be produced from a variety of agricultural products, but is more expensive than methanol. When ethanol is used, the biodiesel can be a highly renewable product.



Source: Van Gerpen et al.

Figure 8. Transesterification reaction.



Source: Tapasvi et al. (2004)

Figure 9. Oil degumming and refining.

The following paragraphs describe the production process for biodiesel (illustrated in Figure 9). Blending vegetable oils with a metallic salt and water will cause gums and other contaminants in the oil to flocculate. The flocculate can be removed as a solid from the oil. These solids can be removed and are typically referred to as "soap stock." The soap stock can be used in cosmetics or other industrial applications. The clarified oil is then remixed with a metallic salt (e.g., sodium or potassium hydroxide) and an alcohol (e.g., methanol or ethanol).

Degumming must take place to remove the phosphatides (the gum-forming materials) from the crude vegetable oil used for biodiesel production. Degumming consists of agitating about 1.5 percent of water with the oil at about 90 °C for 30 minutes, whereupon the phosphatides become hydrated and insoluble in the oil. The phosphatide content differs for the various vegetable oils. Sunflower oils, for example, have approximately 0.5 wt percent phosphatide content. Soybean oils have approximately 1.5 to 2.5 wt percent phosphatide content (Pryde 1981).

Typically, the crude vegetable oil is heated to approximately 70 °C (Tapasvi et al. 2004). Hydratable and non-hydratable phosphatides are removed from the oil using a degumming solution (0.1 percent of 0.85 wt percent phosphoric acid aqueous solution or 2500 ppm citric acid may be used) followed by the addition of soft water equal to 75 percent of the phosphatide content in the crude oil (Hernandez et al. 1996; Erickson 1995). The hydrated phosphatides can be removed by continuous centrifugation. The non-hydratable phosphatides are converted to water-soluble phosphatidic acid through the addition of phosphoric acid, and hydratable phosphatides are formed from the addition of soft water. The contents in the degumming mixing tank are centrifuged to separate the oil from the gums-water mixture. All phosphatide in the form of gums, all unreacted

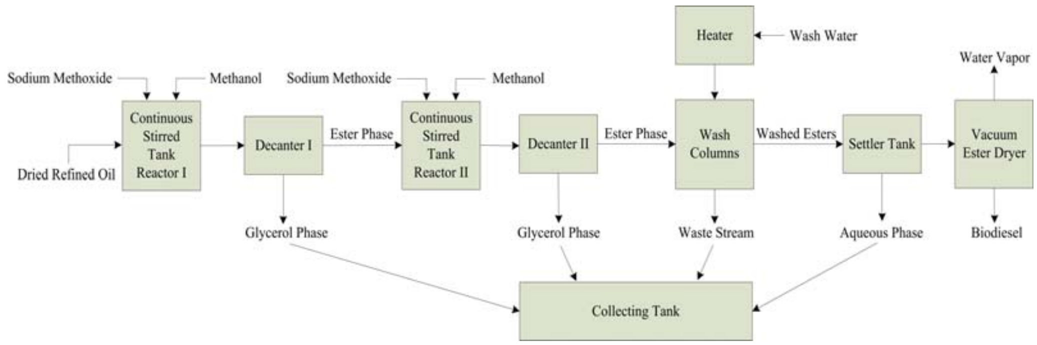
phosphoric acid, and 99.5 percent of soft water added to the mixing tank are recovered in the gums and water separator (Sheehan et al. 1998).

After the degumming process, free fatty acids (FFAs) are removed through an alkali refining step. An aqueous solution of sodium hydroxide (9.5 wt percent NaOH) is added to the refining tank to convert the FFAs in the degummed oil to oil-insoluble soaps. This process is followed by the addition of washwater to dissolve the soaps and the resulting soapstock is removed from the oil using a centrifuge. The amount of washwater added is equal to 15 percent of the mass flow rate of the degummed oil (Sheehan et al. 1998). Typically, 99 percent of the FFAs are converted to soaps by reaction with NaOH. The centrifuge outlet stream is routed to a vacuum oil dryer to remove the remaining water in the oil and the dried degummed and refined vegetable oil is placed into a surge tank for cooling.

Transesterification of the dried, degummed, and refined vegetable oil is the next process step in the biodiesel production process. Figure 10 shows a generalized flow chart. The vegetable oil enters a Continuous Stirred Tank Reactor (CSTR), which is maintained at 65 °C (Tapasvi et al. 2004).

Sodium methoxide serves as a catalyst and is added (as a 10 percent solution in methanol) in an amount equal to 1 percent of the dried degummed and refined oil. Also added is 100 percent excess methanol. The transesterification reaction between the triglycerides and methanol forms methyl esters, or biodiesel, and glycerol at a typical efficiency of 85 percent (Van Gerpen et al. 2003). Additionally, trace amounts of FFAs in the refined oil reacts with sodium methoxide to form soaps and methanol.

The reaction products are separated using a decanter, to separate a glycerol phase (glycerol, methanol, sodium methoxide, soaps) and ester phase (methyl esters, unreacted oil, methanol, soaps). The glycerol phase is sent to a collecting tank and the ester phase is sent to a second CSTR tank. The glycerol phase contains 60 percent of the total methanol in mixture coming from the first CSTR tank, and 10 percent of the total amount of soaps formed from the reaction between the FFAs and the sodium methoxide (Van Gerpen et al. 2003).

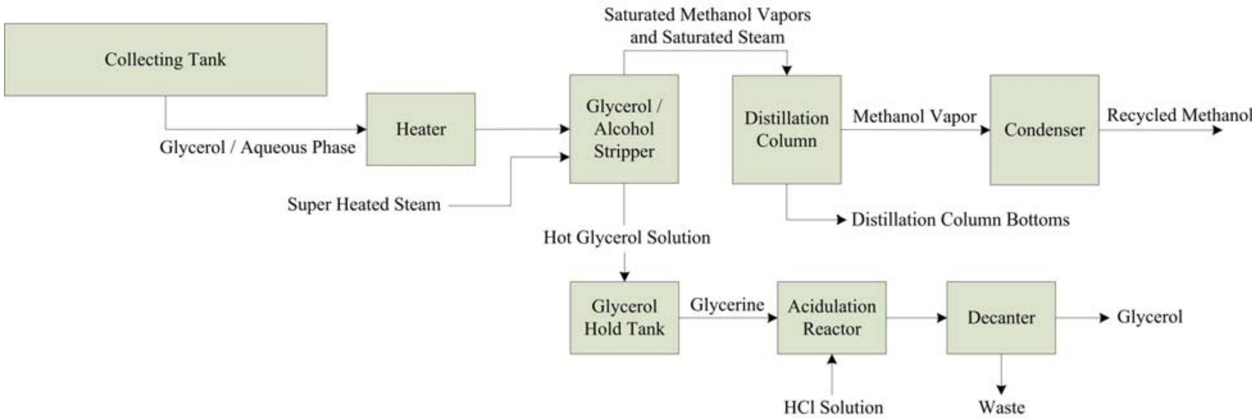


Source: Van Gerpen et al. (2003)

Figure 10. Biodiesel production through transesterfication.

A similar process occurs in the second CSTR tank as the first CSTR tank, where 100 percent excess methanol is again used based on the remaining unreacted triglyceride. The amount of sodium methoxide catalyst added (now as a 10 percent solution in methanol) is equal to that of 1 percent of the triglyceride left unreacted. The glycerol phase is sent to the collecting tank, similar to the first transesterification reaction tank. The glycerol phase coming from the second decanter contains 60 percent of the total methanol in the mixture coming from the second CSTR tank, 10 percent of the total amount of soaps, and all the glycerol and sodium methoxide coming from the second decanter (Van Gerpen et al. 2003). The ester phase from the second decanter is then directed to an ester-washing process.

Ester washing removes impurities in the ester phase, such as methanol, soaps, and free glycerol. This is carried out by washing the ester phase with warm water in wash columns. The amount of washwater added is equal to 20 percent of the methyl esters coming from the second decanter (Sheehan et al. 1998). The waste stream produced in the washing process contains 90 percent of washwater added and 100 percent of the methanol and soaps contained in the ester phase coming from the second decanter, (Sheehan et al. 1998). The waste stream is sent to a collecting tank and the washed ester stream is directed to a settler tank. The remaining aqueous phase is separated from the methyl esters in the settler tank. Next, the ester stream, which at this point contains only 0.5 percent of the initial amount of washwater input (Sheehan et al. 1998), is vacuum dried to remove any trace levels of moisture remaining. Methanol and glycerol are recovered from the biodiesel production process and placed in a collecting tank (Figure 11).



Source: Tapasvi et al. (2004)

Figure 11. Methanol recovery and glycerol refining.

The stream coming from the collecting tank is heated to the normal boiling point of methanol (65 °C) in the heater. The methanol is then stripped from the mixture using super heated steam (at 1 bar pressure and 180 °C) in the glycerol/alcohol stripper. The saturated methanol vapor and steam are typically completely recovered and are subsequently fed into a distillation column to recover pure methanol vapor as distillate. The methanol vapor, which now contains approximately 0.05 percent moisture, is condensed and recycled to the biodiesel production process. Bottoms of the distillation contain glycerol, steam, and other impurities, which typically have no more than 0.5 percent methanol (Sheehan et al. 1998).

The hot glycerol solution from the bottom of the glycerol / alcohol stripper is sent to a glycerol hold tank where it is then mixed with a 10 percent aqueous hydrochloric acid (HCl) solution equal to 50 percent of the glycerin stream (Sheehan et al. 1998). A sodium methoxide catalyst in this stream reacts with HCl to form methanol and sodium chloride (NaCl). Any soaps present in this stream react with HCl to form FFAs and NaCl in the acidulation reactor. A decanter is used to separate glycerol product from the FFAs and other impurities such as unreacted vegetable oil.

The data in Table 6 lists the process inputs and outputs necessary to produce canola and soy methyl esters, as illustrated in two example evaluations using a model developed by Tapasvi et al. (2004). A flow rate basis of 100 kg per hour of crude vegetable oil input was assumed for the analysis.

Table 6. Biodiesel process inputs and outputs.

Process Inputs	Canola oil (kg/hr)	Soybean oil (kg/hr)
Crude oil	100.00	100.00
Methanol into CSTRs	14.31	13.84
Sodium methoxide into CSTRs	10.98	10.84
NaOH (9.5 wt% aqueous solution)	14.86	14.93
HCl (10% aqueous solution)	6.12	6.24
Phosphoric acid solution	0.11	0.11
Process water (total input)	34.49	34.69
Process Outputs	**Canola oil (kg/hr)**	**Soybean oil (kg/hr)**
Biodiesel	94.04	92.81
Methanol recycled	13.70	13.36
Glycerol	10.53	10.28
Water vapor	8.55	8.63
Waste	54.05	55.57

Source: Adopted from Tapasvi et al. (2004) for 100 kg/hr crude oil process.

Note: Composition: 96.0% triglycerides, 0.5% free fatty acids, 2.0% phosphatides, and 1.5% others (unsaponifiable matter); composition: 97.25% triglycerides, 0.5% free fatty acids, 1.25% phosphatides, and 1.0% others (unsaponifiable matter); includes gums and water mix, soapstock, distillation column bottoms, and waste from the glycerol refining decanter.

Cost Overview

Biodiesel production from vegetable oils is a relatively simple process. No technology advances are expected that would significantly change the economics of this process area. Table 7 lists generalized cost information for biodiesel production from vegetable oils.

Table 8 lists summary cost information for the production of canola, mustard, sunflower, and camelina biodiesels in Montana. The cost of manufacture in each instance includes the operational cost from crushing the seeds into oil through biodiesel production. Oil extraction cost estimates were for cold press processing. Note that, two of the three oilseed crushers currently in use in Montana use mechanical press extraction only.

Table 7. Generalized cost information for biodiesel production from vegetable oil.

Plant Size (MGY)	3	5	10	15
Total capital cost (Million $)	3.0 – 3.75	4.8 – 6.25	6.3 – 7.5	7.2 – 9.75
Operating cost ($/gal biodiesel)	0.92	0.5	0.4	0.38

Source: Duff (2004), Tyson et al. (2004) and Shumaker (2003)

Note: Total Capital Cost does not include owners cost – inventory, land, buildings, organizational, etc.; Total Capital Cost does not include glycerol bottoms recovery; Operating Cost does not include cost of feedstock; the hyphenated quantities in row 1 denote that a range was found for the capital cost values for the biodiesel production equipment.

Table 8. Cost to manufacture biodiesel.

Species	Cost of Ingredients ($/cwt)	Cost to manufacture ($/gal)	Expected wholesale ($/gal)
Canola	$12.00 ($5.17)	$2.10	$2.65
Sunflower	$11.00 ($3.94)	$1.97	$2.45
Mustard	$10.50 ($3.88)	$1.85	$2.38
Camelina	$ 8.00 ($1.75)	$1.13	$1.87

Source: Adapted from Johnson (2005) and Johnson (2005a)

Note: Expected price paid by manufacturer (projected grower cost in parenthesis), cwt = 100 lbs; cost of oilseed crushing and biodiesel manufacture based on USDA Value Added Development Grant Feasibility Analysis

This is due in part because they also produce high quality protein and glycerin in addition to the vegetable oil. High quality protein sells for a price of 10 cents per pound, and the glycerin sells for approximately 50 cents per pound. The quality of the meal decreases when higher efficiency solvent extraction techniques are used (Johnson 2005). Thus, a balance can be found in the overall economics when considering revenues derived from all oilseed products.

In biodiesel production, 65 to 75 percent of the finished biodiesel product cost can consist of the cost of seed for oil processing. Reductions in oil seed costs for use in biodiesel production can have a discernible impact on the overall cost of biodiesel production. Researchers at Montana State University's Northwestern Agricultural Research Center (ARC) have been developing a low input (i.e., low investment) crop – camelina.

Table 9 lists the projected cost estimates for the production of canola and camelina biodiesels produced in Montana (Pilgeram 2005; Johnson

2005). Since the values from Table 8 were used to construct Table 9, the following assumptions were made in this economic projection:

- Canola yields 37 lbs of oil per 100 lbs of seed.
- Camelina yields 35 lbs of oil per 100 lbs of seed.
- Density of canola oil is 7.645 lb/gal.
- Density of camelina oil is 7.56 lb/gal.

Camelina is being developed as a low input investment crop. Dry land camelina production costs have been estimated at approximately $25 per acre (via direct cutting) and $35 per acre (via swathing). For this report, a conservative production cost estimate of $40 per acre was used. Canola investment in Montana has been approximately $125 per acre. Yields for camelina at Northwestern ARC have ranged from 1,925 lbs/acre to 2,215 lbs/acre, though this analysis considered a conservative average of 1,500 lbs/acre. Canola yields at the same location on dry land have averaged 1,667 lbs/acre. The selling price of camelina could have been set as low as $0.07 per pound of seed, which would compete with canola. However, the selling price of $0.08 per pound was set such that it would compete with wheat as a preferred crop to grow in Montana. With these assumptions, the price of the vegetable oil (at this point is still contained in the seed) is about $2.48/gal for canola and roughly $1.73/gal for camelina.

Table 9. Estimated biodiesel production costs.

	Canola	Camelina
Crop input cost ($/acre)	$125	$40
Average seed yield (lb/acre)	1667	1500
Seed production cost ($/lb)	$0.0750	$0.0267
Farmer selling price ($/lb)	$0.12	$0.08
Equivalent oil (in seed) price ($/gal)	$2.48	$1.73
Gross return to farmer ($/acre)	$75	$80
Seed crushing and biodiesel production cost ($/gal)	$0.64	$0.64
Biodiesel manufacturing cost ($/gal)	$3.12	$2.37
Excise taxes ($/gal)	$0.42	$0.42
Blender tax credit ($/gal)	-$1.00	-$1.00
Wholesale markup ($/gal)	$0.11	$0.08
Wholesale price ($/gal)	$2.65	$1.87
Retail markup ($/gal)	$0.16	$0.11
Retail price ($/gal)	$2.80	$1.99
Source: Pilgeram (2005); Johnson (2005).		

The seed crushing operation and biodiesel production costs combined for this analysis was considered to be independent of the type of oil used for production. The crushing and biodiesel production costs were estimated to be $0.64/gal of biodiesel produced, which brings the manufacturing cost to $3.12/gal for canola and $2.37/gal for camelina. Excise taxes of $0.42/gal of biodiesel were added and a tax credit was applied, namely a Federal Biodiesel Incentive provided by the American JOBS Creation Act (H.R. 4520) signed into law in October 2004. This tax credit created for biodiesel blenders can be used to the amount of $1.00/gal for agri-biodiesel (biodiesel derived solely from virgin oils, including esters derived from virgin vegetable oils from corn, soybeans, sunflower seeds, cotton-seeds, canola, crambe, rapeseeds, safflowers, flaxseeds, rice bran, and mustard seeds, and from animal fats), and $0.50/gal for other biodiesels (those that meet the registration requirements for fuels and fuel additives established by the U.S. Environmental Protection Agency (USEPA) under section 211 of the Clean Air Act, and the requirements of the American Society of Testing Materials D6751). The example data in Table 9 assume a $1.00/gal subsidy.

The wholesale markup was considered to be 3 percent, and the retail markup was taken as 6 percent. Thus, the wholesale price of canola was $2.65/gal, and for camelina the wholesale price was $1.87/gal. Finally, the retail price for biodiesel produced from canola and camelina are projected in this example to be $2.80/gal and $1.99/gal, respectively.

Biodiesel Characteristics

Table 10 lists selected chemical and physical properties for the biodiesels derived from the six vegetable crops. For comparison, the same properties for petroleum diesel, alcohol, and soy oil were also included. Relative to petroleum diesel, biodiesel has:

- comparable heating values
- a higher flash point
- similar flow characteristics (i.e., viscosity)
- comparable hydrogen content
- lower sulfur content.

Table 10. Composition of various biodiesels, diesels, and alcohols.

Composition	Canola Oil Methyl Ester	Canola Oil Ethyl Ester	Rapeseed Methyl Ester	Rapeseed Ethyl Ester	Sunflower Methyl Ester	Sunflower Ethyl Ester
Hydrogen (wt %)	11.9–12.3	12.1	9.0–12.4	12.6–12.8		
Carbon (wt %)	77.2–77.7	77.6	77.7–80.7	77.8–78.2		
Oxygen (wt %)	10–10.8	10.3	9.9–10.2	9.2–9.4		
Sulfur (ppm)	4–90		3–300	10–320		<200
Density (20 °C, lb/gal)					7.29–7.39	7.29
Viscosity (40 °C, cS)	3.8		6.7		4.2–5.7	4.9
Viscosity (20 °C, cS)	7		8		15	
Cloud Point (°C)	(-3)–(-1)		(-6)–(-2)	(-4)	(-2.8)–1	
Pour Point (°C)	(-4)		(-16)–(-9)	(-18)	(-4)	
Flash Point (°C)	162–163		84–392	406	183	>100
Heating Value (BTU/lb)						
Gross (HHV)			17,369–17,412	17,498	16,853–17,197	16,724–17,713
Net (LHV)	17,240		15,993–16,251	16,337	16,208–16,380	16,552

	Soybean Methyl Ester	Soybean Ethyl Ester	Diesel 1	Diesel 2	Ethanol	Methanol
Hydrogen (wt %)	12–12.4		12.7–13.6	12.7–13.1	13.13	12.58
Carbon (wt %)	76.4–78.6		85.5–86.8	86.0–86.9	52.14	37.49
Oxygen (wt %)	9.4–11.4		0.0–0.96	0.0–1.32	34.73	49.93
Sulfur (ppm)	120		35–450	230–2500		
Density (20 °C, lb/gal)	7.29–7.39	7.09	6.84	6.93–7.17		
Viscosity (40 °C, cS)	4.0–5.7	4.4–4.7	1.5–1.8	2.0–4.3	1.1–1.4	
Viscosity (20 °C, cS)				3.5–3.8		
Cloud Point (°C)	(-5)–3	1	(-54)	(-18)–(-9)		
Pour Point (°C)	(-13.3)–2	(-4)	(-58)	(-33)–(-18.5)		
Flash Point (°C)	160–236	174	50	52–190	8	10
Heating Value (BTU/lb)						
Gross (HHV)	17,111–17,154	17,197	19,776	19,475–19,690	12,683–12,812	9,630–9,802
Net (LHV)	15,907–17,154	16,251	18,616	18,315–18,745		

Source: Adapted from Przybyiski (2000), Peterson et al. (2001), De Winne (2004), Lele (2005), Sharp (1996), Tahir et al. (1982), Megahed et al. (2004), Hawkins and Fuls (1982), Pischinger et al. (1982) and Strayer et al. (1982).

Notes: Insufficient data for Crambe, Mustard, Safflower seeds.

Synthesis Gas Production from Biodiesel

Syngas is often preferred second only to pure hydrogen for use in many power generation systems, namely in high temperature fuel cells (solid oxide and carbonate) and gas turbines.

Reforming processes can be used to convert hydrocarbons into hydrogen (H_2) rich syngas. The selection of a particular reforming technology must be carefully matched to the power generation technology employed. In addition to hydrogen, the remaining components in reformed fuel streams are designed to be either carbon monoxide (CO) or carbon dioxide (CO_2), depending on the selected reformer technology. Therefore, in fuel cell applications, for example, this is very important since low temperature fuel cells may be poisoned by CO, whereas high temperature fuel cells use CO as fuel. A prior study and market survey of reformers for the conversion of vegetable oil or biodiesel into syngas (Adams et al. 2004) concluded that catalytic partial oxidation (CPOX) reforming was the most suitable technology for the production of syngas from canola oil or other biodiesels for use with high temperature fuel cell systems.

The reformation of vegetable oil directly into syngas is not a well studied or practiced operation. However, reforming technologies and their applications for other feedstocks are well known and documented. While many technical unknowns exist, the expectation is that biodiesel fuel reformation is a direct conversion pathway. Reformer equipment suppliers generally stated that the reformation of biodiesel should require little or no modification to a reformer system that can convert conventional petroleum diesel fuel into syngas (Barringer 2005; Chellappa 2005).

Several different types of reforming processes are available, including:

- steam reforming
- partial oxidation reforming
- auto-thermal reforming
- thermal decomposition
- plasma-based reforming.

The following sections describe these reforming processes.

Steam Reforming

Steam reformation (SR) technology has a long history and is widely deployed in the chemical processing industry. This technique is generally considered to be the most cost effective for large-scale hydrogen production because of its ability to obtain unrivaled levels of efficiency. Steam reformation is an endothermic reaction whereby steam and heat is applied to the fuel to form a hydrogen rich fuel stream. A generic equation for steam reformation of oxygenated fuel is:

$$C_nH_mO_p + (2n - p)H_2O \rightarrow nCO_2 + (2n - p + \tfrac{m}{2})H_2$$

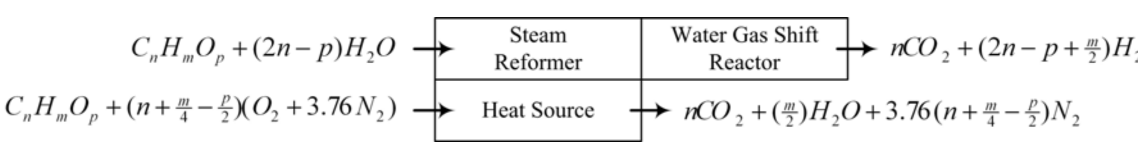
Often the steam reformation reaction is used at large-scales to reform methane (CH_4), where the stoichiometric reaction product favors CO versus $CO_{2,}$ which is in contrast to the reformation of oxygenated fuels. Also, the steam reformation reaction is accompanied by the water gas shift reaction:

$$CO + H_2O \leftrightarrow CO_2 + H_2$$

Steam reformer effluent generally contains a mixture of H_2, CO, and CO_2. The steam reformation reaction is strongly endothermic and requires significant heat input, where a combustion vessel is often placed adjacent to the reformation vessel. A generic equation for the combustion of oxygenated fuels is:

$$C_nH_mO_p + (n + \tfrac{m}{4} - \tfrac{p}{2})(O_2 + 3.76N_2) \rightarrow nCO_2 + (\tfrac{m}{2})H_2O$$

Figure 12 shows a general schematic of steam reformation.



Source: Ahmed and Krumpelt (2001)

Figure 12. Steam reformation process.

Steam reforming equilibrium is favorable at low pressure, high temperature, and high steam ratio. The steam reforming process is highly dependant on the reactor's internal temperature profile where a reactor will operate at peak efficiency when the temperature profile is uniform and at the desired temperature. This design constraint limits passage cross section

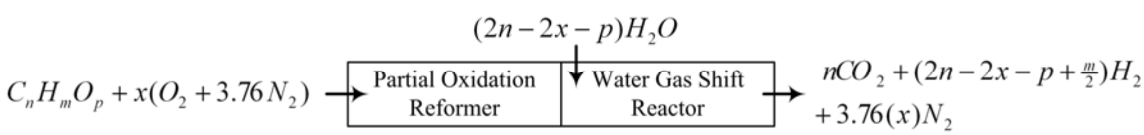
area, where pressure drop and wall temperature profiles determine the length requirement. Reactor tubes are often bundled in parallel to abide by all of these constraints. A large disadvantage of conventional steam reformers is that heat transfer limits them so that they are bulky in size, have a slow start-up time, and have less ability to react to transient operation. Furthermore, the loss of steam to a steam reformer will cause certain failure.

Partial Oxidation Reforming

Partial oxidation (POX) is a technique that partially combusts a fuel stream with a sub-stoichiometric amount of air. Fuel flexibility is an advantage for the POX approach, for the process make sit relatively easy to convert heavy hydrocarbon fuels (Pastula et al. 2001). POX is known for its simplicity, reliability, short start-up time, and good load following characteristics. A disadvantage of the POX reaction is that it is more selective to CO than is the steam reforming reaction. A general equation for partial oxidation of oxygenated fuels is as follows:

$$C_nH_mO_p + x(O_2 + 3.76N_2) + (2n - 2x - p)H_2O \rightarrow nCO_2 + (2n - 2x - p + \tfrac{m}{2})H_2 + 3.76(x)N_2$$

Figure 12 shows A general schematic of partial oxidation.



Source: Ahmed and Krumpelt (2001)

Figure 13. Partial oxidation reformation process.

Although Figure 12 shows water input as well as in the POX equation, the reaction does not require the input of water. Partial oxidation reformers can use more than one reaction pathway, commonly referred to as direct or indirect pathways. In one form of the direct pathway, the entire fuel stream is fed a sub-stoichiometric amount of oxidant (air) in a single chamber, where the oxygen deficient POX reaction generally takes place in the presence of a catalyst. In another form of the direct POX pathway, steam is added subsequent to the POX reaction to facilitate further reformation of the fuel stream by steam reformation. The air input of this con-

figuration is adjusted to accommodate for the additional, endothermic steam reformation.

In the indirect POX pathway, three principle reactions generally take place: the combustion, steam reformation, and dry (CO_2) reformation. Dry or CO_2 reformation can be represented as:

$$C_nH_m + nCO_2 \rightarrow 2nCO + (\tfrac{m}{2})H_2$$

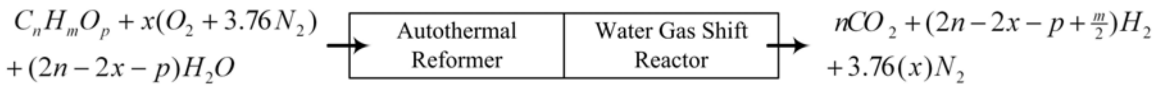
In this configuration, a different catalyst and reaction chamber is generally used for each reaction that takes place. In the first chamber, a small and separate portion of the fuel stream is completely oxidized into combustion products, carbon dioxide, heat, and water. Subsequently, this combusted gas stream is fed into a chamber containing fresh fuel. With the aid of one or more catalysts (typically), the fresh fuel is reformed by the combustion products via steam and dry reformation. A direct type POX reformer may have a startup time on the order of a few minutes, whereas an indirect type POX reformer can have a startup time of an hour (Pastula et al. 2001).

Auto-Thermal Reforming

Autothermal reformers (ATR) have been developed primarily for operation with methanol and gasoline. This reformer type may be thought of as a hybrid of the partial oxidation and steam reformer types in that reactions from both reformation techniques take place. Steam is delivered to the reformation chamber with fuel and a sub-stoichiometric amount of oxidant (often air):

$$C_nH_mO_p + x(O_2 + 3.76N_2) + (2n - 2x - p)H_2O \rightarrow nCO_2 + (2n - 2x - p + \tfrac{m}{2})H_2 + 3.76(x)N_2$$

The exothermic reaction of a small portion of the fuel and the oxygen provides heat for the endothermic steam reformation reaction. The ATR reaction is more selective to CO_2 than CO (making it more compatible with low temperature fuel cells versus high temperature fuel cells). One of the primary drivers of development for this reformation technique is that of the automotive application. This is due to the fact that the PEM fuel cell has been selected by most fuel cell vehicle designers to provide primary power, leading to the selection of the auto-thermal reformer. Figure 14 shows a general schematic of auto-thermal reformation.



Source: Ahmed and Krumpelt (2001)

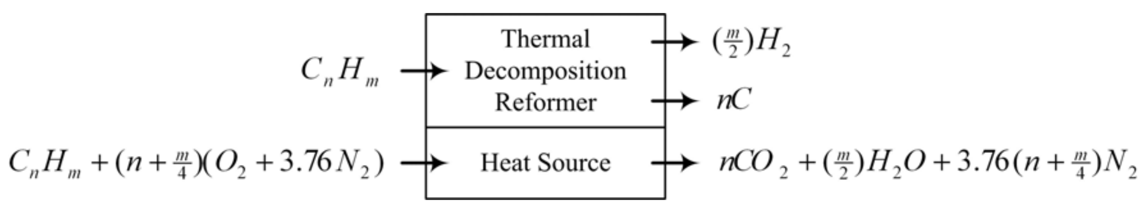
Figure 14. Autothermal reformation process.

Thermal Decomposition

Thermal decomposition reformers (TDR) use heat, such as with pyrolysis techniques, to break down higher hydrocarbon chains into their base components.

$$C_nH_m \rightarrow nC + (\tfrac{m}{2})H_2$$

This technique has a long history and has been used to convert relatively dirty fuels into clean fuels. Figure 15 shows a general schematic of thermal decomposition.



Source: Van Gerpen et al. (2003)

Figure 15. Schematic of thermal decomposition reformation process.

Plasma-Based Reforming

Significant development of a plasma-based reformer system has taken place at Massachusetts Institute of Technology's Plasma Science and Fusion Center. Bromberg et al. (1999) report that the non-homogeneity of biofuels makes reformation of those materials difficult with catalytic reactors. This motivated the MIT team to develop a plasma-based partial oxidation (POX) reformer system that does not require catalyst materials. They have documented experiments with several liquid fuels, including commercially available (edible) canola and corn oil, with promising results. Table 11 lists the reformation characteristics of iso-octane (gasoline simulant), diesel fuel, canola oil, and corn oil.

Table 11. Preliminary plasma-based POX reformation characteristics.

	Old Reactor Generation		New Reactor Generation		
	Iso-Octane	Canola Oil	Diesel	Canola Oil	Corn Oil
Plasmatron Parameters					
Current (Amp)	18		18		
Voltage (VDC)	140		130		
Power (kW)	2.52		2.34		
Flow Rates					
Fuel (g/s)	0.33	0.3	0.4	0.25	0.47
Air into Reactor (g/s)	0.96	0.88	0.9	0.88	0.9
Air Additional (g/s)	0.55	0.34	0.64	0.38	0.6
Output Gas Composition					
H2 (Vol. %)	22	25.6	23.5	22.5	23
O2 (Vol. %)	0	–	0.3		
N2 (Vol. %)	53		44		
CH4 (Vol. %)	3	1.7	0.03	3.1	2.6
CO (Vol. %)	15	26	23	21	18.6
CO2 (Vol. %)	2	0.3	0.1	2.7	2.1
H2 + CH4 Yield (%)	100		95		
H2 Yield (%)	78	92	95	82	84
Energy Consumption					
MJ/kg H2	62	58	50	61	55
MJ/mole Fuel	0.87	2.21	1.19	2.5	
Source: Adapted from Bromberg et al. (1999).					

Two different reformer reactor generations were used to test the various fuels, the "Old" and "New" generation reactors, as noted in Table 11. The two primary differences between the generation reactors were that the reactants in the Old generation experiments underwent significantly more preheat than did the reactants in the New generation experiments. Also, the New generation reactor was reported to have had design/hardware improvements over the Old generation reactor. The data in Table 11 reflects both of these competing variations.

The near term target application for plasma-based reforming is on-board fuel reformation of gasoline and diesel, where reformate would be fed directly into the main fuel line of an automotive engine. Key issues for further development of this reformer technology include increased conversion efficiency, lower input power requirement, extended electrode life

(currently limited to about 1000 hours), shorter necessary residence times, better thermal management, and increased control capabilities (Bromberg et al. 1999).

Other Reformer Initiatives

A few other groups are investigating the direct reformation of vegetable oils – or their biodiesel corollaries – into a high hydrogen content synthesis gas. The efforts of these groups are highlighted below. In general, however, Ross et al. (2003) conclude that for fuel cell and other power generation applications, the technological status of vegetable oil and biodiesel reformation is in its infancy.

Marquevich (2000) reported that sunflower oil was successfully reformed using a steam reformation technique using similar commercial nickel-based catalysts and process conditions to that of conventional steam reforming of naphtha. However, it was also reported that carbon formation began in as early as 14 hours of operation. Additionally, Marquevich (2001) stated that the steam reforming of sunflower, rapeseed, corn, and soybean oils at the same catalyst temperature and steam-to-carbon ratio showed that conversion of vegetable oil into hydrogen rich gas does not depend on the type of vegetable oil.

Intelligent Energy Systems, Albuquerque, NM, a reformer equipment supplier, reported that they had reformed B100 soy biodiesel into fuel cell quality gas via steam reformation. They report that there were some fuel cell complications associated with this experiment, which ultimately forced a capacity reduction of both the PEM fuel cell system and steam reformer system (Chellappa 2005).

Idatech, LLC (located in Bend, OR) is another fuel reformer equipment designer / manufacturer that has experimented with the steam reformation of biodiesel fuel. It was reported that they had carried out a few attempts to convert canola biodiesel into syngas using a steam reformation technique (Zinner 2005). These catalyst testing experiments were said to have been unsuccessful, each of which suffered from rapid carbon formation. Idatech reported that their reformer was debilitated by carbon blockage in less than 30 minutes of operation and during that time reformation did not occur.

SOFCo-EFS, Alliance, OH, has expressed confidence that they could reform any of the various biodiesels or blends of biodiesels into syngas (Barringer 2005). They have been developing fuel processors for high and low temperature fuel cell systems for the past 10 years. Currently they are developing an auto-thermal reformer for low temperature fuel cell systems, and a partial oxidation reformer for high temperature fuel cell systems. SOFCo-EFS has carried out an extensive investigation of distillate fuel processing (Jet-A, JP-8, and diesel fuels with 7 ppm sulfur) with the steam, auto-thermal, and partial oxidation techniques.

Table 12 lists these test results, which show the fuel conversion efficiencies of the three mentioned reformation technologies. Table 12 also lists common fuel and steam consumption characteristics of the various reformer technologies.

Table 12. Fuel reformer operating characteristics.

	Fuel Consumption	Steam Consumption	Steam-to-Carbon Ratio	Percent Fuel Conversion
Steam	1.00	1.00	3.00	97.5
ATR	1.10	0.56	1.50	
CATR			2.8 – 3.7	99.0
POX	1.07	0.24	0.68	
CPOX	0.93	0.07	0.25	98.0
Source: Adapted from Budge et al. (2004) and Sundset et al. (1994).				

Cost Overview

This section presents a cost analysis of reforming technologies, which addresses the equipment necessary to produce syngas only. Additional equipment generally used to produce pure hydrogen from syngas such as water gas shift, preferential oxidation reactors, and or hydrogen separation membranes were not included in the capital cost estimates.

Weinert (2005) presented data on the capital cost of natural gas steam reformation equipment derived from industry. In these cost estimates, Weinert noted that the number of reformer units produced per year was “low” and that purification equipment (CO cleanup) was not included. It was not specified whether or not sulfur removal equipment was included in these capital cost quotes, though it is probable that it was included. The hydrogen flow rate capacity of the reformers listed in Table 13 range from

1.5 kg/hr to 9.0 kg/hr. Weinert (2005) gathered a very wide range of capital cost data by survey (Table 13). For the purposes of this study, an average normalized cost of 135,000 $/kg/hr (which does not include carbon monoxide removal equipment) will be assumed as the present day natural gas steam reformer capital cost and will be applied to biodiesel reforming.

Table 13. Capital cost for natural gas steam reforming equipment.

Hydrogen Production Capacity (kg/hr)	Total Capital Cost ($2004)	Normalized Capital Cost ($/kg/hr)
1.5	372,000	248,000
6.25	200,000	32,000
9.0	1,116,000	124,000
Source: Adapted from Weinert (2005).		

Reliable and consistent capital cost data for the remaining reformer technologies, i.e., auto-thermal, partial oxidation, and catalytic partial oxidation, analyzed as part of this study are not available in the public domain at this time, regardless of the fuel used in the reformer. However, a comparative study on the cost of various natural gas reformation technologies reported that the capital cost of the natural gas steam reformer technology was the highest of all reformer technologies (Sundset et al. 1994); therefore, its relative capital cost was taken as unity (Table 14). The homogenous partial oxidation technology (no catalyst) was rated as the second most costly after the steam reformation technique, followed by the autothermal and catalytic partial oxidation technologies. It should be noted, however, that the catalytic partial oxidation (CPOX) cost estimate provided by Sundset et al. (1994) was said to be less precise than the other cost estimates, since it was based only on an idealized case. It was reported that CPOX reformation was an emerging technology during the work of Sundset et al. (1994). Table 14 lists the extrapolated capital cost data for the remaining present-day reformer technologies, which were calculated using the normalized and averaged natural gas steam reformer cost figures derived from Weinert (2005), in conjunction with the comparative natural gas reformer costs taken from Sundset et al. (1994).

Table 14. Relative capital cost of reformation technologies.

Reformer Type	Relative Capital Cost	Current Capital Cost ($/kg/hr)	Projected Capital Cost ($/kg/hr) (Year 2011)
Steam	1.0	135,000	1,233
Partial oxidation	0.48	64,800	592
Auto-thermal	0.34	45,900	419
Catalytic partial oxidation	0.26	35,100	321
Source: Adapted from Arthur D. Little (2001) and Sundset et al. (1994).			

Table 14 also includes a capital cost projection for reformer technologies based on a published study by Arthur D. Little (2001) for the homogeneous partial oxidation reformer technology. Arthur D. Little projected a capital cost for the year 2011 with the assumption that 500,000 units per year would be produced. In contrast to the previous reformer cost estimates already discussed, this cost estimate was for sulfur-free Fischer-Tropsch diesel fuel as the reformer input. The original estimate published by Arthur D. Little (2001) was normalized in terms of net fuel cell electric power output, as opposed to the hydrogen mass flow rate produced as shown in Table 14. To convert this figure, it was calculated that a 5 kWe (net) fuel cell system will consume up to approximately 0.5 kg/hr of hydrogen. Thus, the future capital cost projection for the POX reformer is shown as approximately $592 / kg/hr. This figure assumes that sulfur removal equipment is not needed, as do the other reformer technology cost projections. Similar to the Current Capital Cost figures shown in Table 14, cost extrapolations were made for the remaining reformer technologies using the Relative Capital Cost percentages published by Sundset et al. (1994).

Summary

Chapter 2 reviewed and assessed three important process steps: (1) the extraction of the oil from the seed crop, (2) the conversion of that oil to its biodiesel corollary, and (3) the reforming of that biodiesel into a hydrogen rich synthesis gas (or syngas). An understanding of the contribution of these process steps is important to an understanding of the overall economics of using agriculturally derived fuels from Montana for defense and civilian power generation applications.

Seed Delivery / Storage

↳ **Crushing / Oil Extraction**

↳ **Conversion to Biodiesel**

↳ **Reforming to Synthesis Gas**

↳ ↳ **Synthesis Gas Used for Power Generation**

The findings reported above indicate a high state of technology maturity for oil extraction and conversion of the extracted vegetable oil to its biodiesel corollary. Conversely, the state of technology maturity for reforming technologies applied to vegetable oils or their biodiesel corollaries is low. The potential for improvements in economic performance is highest for reforming technologies due mostly to its early stage of technology maturity (Table 15).

Table 15. Potential for improvements in economic performance for reforming technologies.

Process Step	Technology Maturity	Potential for Economic Improvement
Oil extraction	High	Moderate
Conversion to biodiesel	High	Low
Reforming to syngas	Low	High

A more fully developed understanding of the technology issues associated with vegetable oil and biodiesel reforming is needed. This understanding could be most effectively achieved with a short-term emphasis on reformer technology laboratory investigations rather than field demonstration initiatives requiring reformed fuels. These reformer laboratory investigations should research various reformer technologies suitable for application with Montana-based agricultural crops. In addition, these investigations should consider the power generation technology to be applied, e.g., fuel cell, micro-turbine, combustion engines, etc., to the produced syngas.

The current capital cost of the equipment necessary to produce vegetable oil, biodiesel, and syngas from biodiesel was evaluated and compared based on a scenario constructed with the following assumptions:

- All vegetable oil produced from a mechanical oilseed crushing plant (no solvent extraction) is used to make methyl ester biodiesel.
- All biodiesel that is produced is then used to produce hydrogen-rich syngas using the reformation technologies previously discussed.

- All plant equipment operates an average of 330 days per year.
- The reduction in reformer system capital cost due to increased scale of operation can approach 60 percent when production volumes are low (Weinert 2005). Thus, given that the Current Capital Cost figures are for relatively small fuel reformer systems, a 60 percent reduction in capital cost is assumed for the current large-scale reformer scenario.
- Additional equipment needed to accommodate liquid fuel as opposed to natural gas can increase the Current Capital Cost of the reformer system equipment by approximately 15 percent (Arthur D. Little 2001).
- Sulfur removal equipment in the reformer system was not included in this analysis, which is expected to reduce the Current Capital Cost data for the reformer system by approximately 25 percent (Arthur D. Little 2001).
- The average Current Capital Cost figure for the natural gas steam reformer ($135,000/kg/hr) was used as the reformer cost basis for this cost analysis. To couple this cost figure for use with biodiesel, the natural gas steam reformer was normalized based on an input fuel rate, or approximately $62,000/kg/hr of consumed natural gas fuel. Thus, assuming that the cost of the reformer equipment is the same for natural gas and biodiesel synthesis gas (e.g., 1 kg/s of natural gas requires the same reformer size as 1 kg/s of biodiesel synthesis gas), the Current Capital Cost of the biodiesel reformer system can be approximated.

Figure 16 shows the results of this scenario for the biodiesel reformer system. This illustrates that reformer capital costs are a significant part of the overall capital cost requirement for converting oilseed crops into a synthesis gas for power generation. This is true for other reformer applications, as it is reported that the syngas production step is the most expensive in the production of methanol from natural gas (Sundset et al. 1994; and Petroleum Energy Center 1999), accounting for approximately 50 percent to 60 percent of the total plant cost.

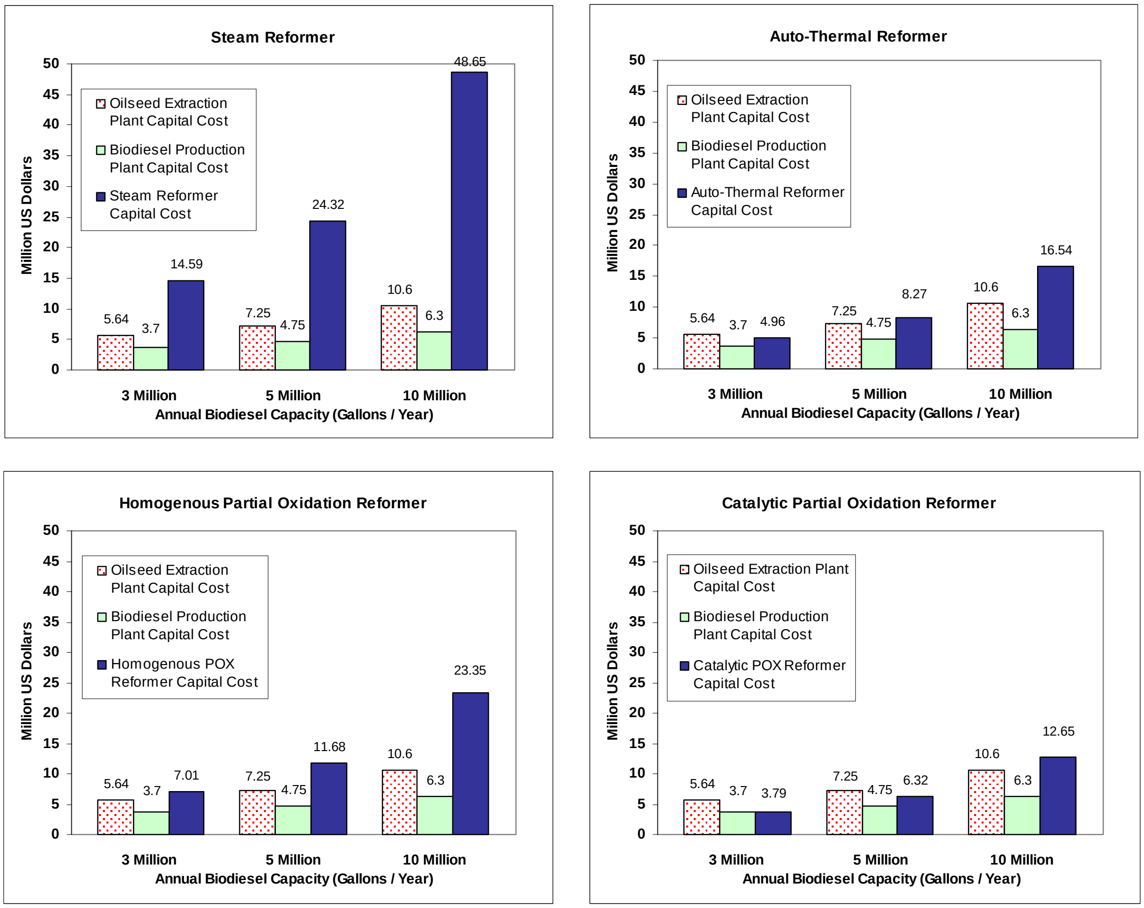


Figure 16. Capital cost estimates for oil, biodiesel, and synthesis gas production.

Identification of Commercialization Pathways

This study evaluates the issues related to the use of Montana-based oilseed crops for power generation in defense and civilian applications. Agriculture is the largest industry in the state of Montana, representing approximately 3.8 percent of its gross state product. Approximately 8.7 percent of the state's work force is employed in agriculture, which uses 64 percent of the land area of Montana. Current regional and national interest in the production and use of renewable fuels for power generation applications suggests that Montana's agriculture industry could be well positioned to participate in an emerging market opportunity important to both national defense and homeland security.

Furthermore, Montana presents a number of unique challenges for defense and civilian power generation applications, which include the fact

that Montana locations are characteristically: small and remote, reside at a high altitude, and are affected by a seasonally cold climate. Overcoming the technical challenges posed by these characteristics merits consideration not only for defense and civilian power generation in Montana, but also for corollary applications in other locations throughout the United States and around the world.

Chapter 2 of this report assessed the major technical sequences for producing biodiesel fuels for defense and civilian power generation applications. The major elements of the technical sequence are:

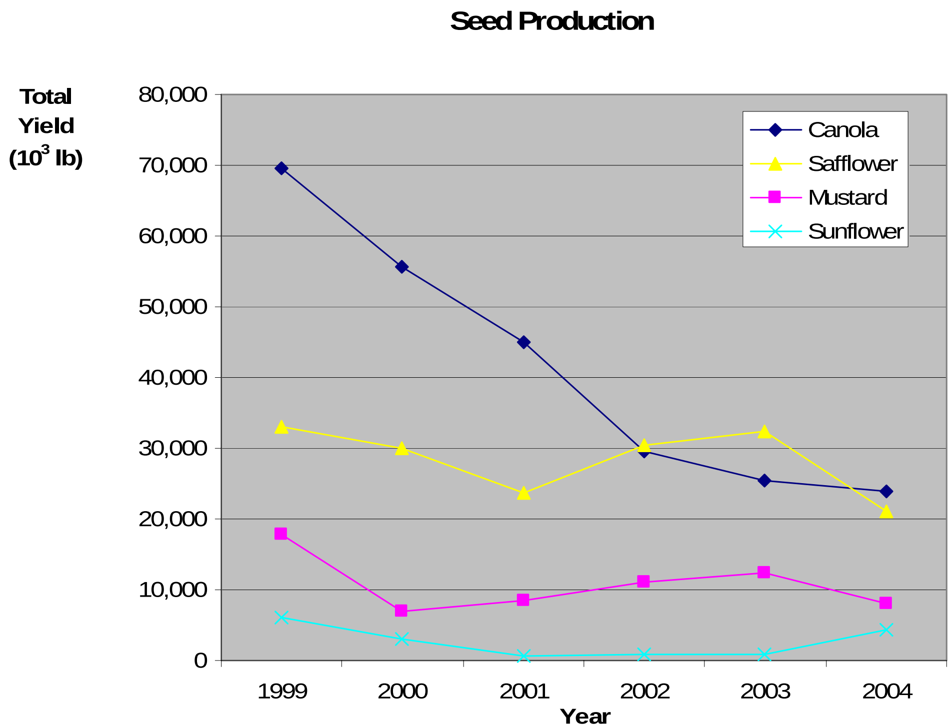
Crop Production / Seed Delivery / Storage
↳ **Seed Crushing / Vegetable Oil Extraction**
↳ **Conversion of Vegetable Oil to Biodiesel**
↳ **Reforming Biodiesel to Synthesis Gas**
↳ ↳ **Power Generation Applications**

The following paragraphs assess various commercialization issues related to each step of this technical sequence, considering current initiatives and market dynamics. Observations will be shared, including recommendations to overcome potential commercialization barriers.

Oilseed Crop Production in Montana

Figure 17 shows expected harvest characteristics for Montana oilseed crops, including canola, mustard, safflower, and sunflower. (Sufficient data were not available to include crambe and rapeseed in this list.) Although Montana produces significant amounts of flax, this report does not consider flax because its oil yield is generally too low for use as an energy crop. Also, while Montana does have some experimental-size soybean plantings, soy was not considered in this report because soybeans are not an economically important Montana oilseed crop (because soy does not do well in cool weather climates like Montana [Johnson 2005]).

Yields plotted in Figure 17 are much lower than long term average yields due to recent drought conditions that have been experienced in Montana. For example, the 6-year average for the canola harvests is calculated to be 1,077 lb/acre, in contrast to long term average yields for canola, which are approximately 1,667 lb/acre (Johnson 2005).



Source: Adapted from: http://www.nass.usda.gov/mt/crops/
Notes: Total harvest statistics includes hulls.

Figure 17. Projected annual oilseed harvest statistics for Montana oilseed crops.

Adams (2006) calculated the theoretical yields of Montana grown vegetable oils and the hydrogen they could generate. This study updated these calculations; Figure 18 and Table 15 present the expected yields, including canola, crambe, mustard, rapeseed, safflower, and sunflower.

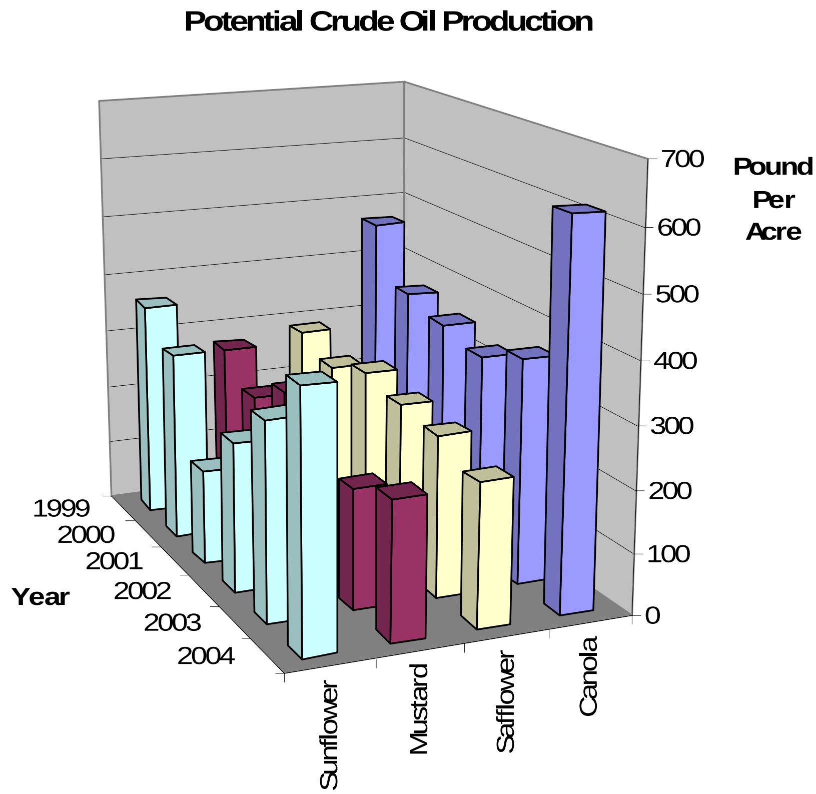


Figure 18. Expected oil yield from oilseed harvest.

Table 16. Expected oil and hydrogen production from Class I and II land in Montana.

Crop	Acres Planted	Seed Yield (lb/acre)*	Seed Production (million lb)	% Oil Yield**	Crude Oil Recovered (million lb)	Biodiesel Yield (million gal)	Total H_2 Production (million lb)
Canola	110,000	1,075	118.3	0.39	46.1	5.9	5.1
Crambe	80,000	690	55.2	0.32	17.7	2.3	2.0
Mustard	400,000	690	276	0.32	88.3	11.4	9.8
Rapeseed	65,000	1,075	69.9	0.39	27.3	3.5	3.0
Safflower	100,000	785	78.5	0.34	26.7	3.4	3.0
Sunflower	65,000	715	46.5	0.42	19.5	2.5	2.2
Total per annum			644.4		225.6	29.0	25.1

*Adopted from Table 3 and updated
**% pounds of oil yield per pounds of seeds

The seed yield data in Figure 17 is adopted from the theoretical yields of Table 3, representative of the dry weather conditions of Montana. Due to insufficient seed yield data, it was assumed that rapeseed would have roughly the same seed harvest yields to that of canola. Similarly, crambe

was assumed to have approximately the same seed yield as mustard. The biodiesel yield calculations assumed that 94 lbs of biodiesel would be produced for every 100 lb of input crude oil (Tapasvi et al. 2004). All calculations assumed a biodiesel density of 7.3 lb/gal. The hydrogen production calculations considered the partial oxidation technique, and a 98 percent hydrogen conversion efficiency (Budge et al. 2004).

Based on the presented results (Table 16), the seed, oil and hydrogen yields are highest for canola and rapeseed (a canola variety). Differences are due to saturation of the oil derived from each crop planted. Other changes could result from process efficiencies that would affect the yields of oil recovery or hydrogen production at each stage of syngas production.

Table 17. Expected oil and hydrogen production per acre.

Crop	Crude Oil Recovered (lbs/acre)	Biodiesel Production (gals/acre)	Total H_2 Production (lbs/acre)
Canola	419.3	54.0	46.4
Crambe	220.8	28.4	24.4
Mustard	220.8	28.4	24.4
Rapeseed	419.3	54.0	46.4
Safflower	266.9	34.4	29.5
Sunflower	300.3	38.7	33.2

Using only the maximum production lands with optimum growing conditions (Class I lands), the hydrogen production would amount to approximately 10.7 million lb annually. However, if variables were relaxed to account for lands with some limitations (e.g., Class II lands), potential oil production could be increased to more than 225 million lb, resulting in an expected hydrogen production of 25 million lb. Maximum production represents maximum input including Class I soils, high rainfall or irrigation and optimum frost-free period. Class II lands involve production on lands of low productivity (lower fertility, salt or low rainfall). Oilseed crops will be competing for Class I lands with other crops. Class II lands are less competitive and more likely to be used for oilseed production.

Currently, research is being conducted on alternative, high yield and low cost oilseed crops such as camelina. There are 1,000 acres planted with camelina seed in Montana, mostly through the Great Northern Growers Cooperative. This planting is expected to yield 1.5 million lb of seed con-

taining approximately 40 percent oil. It was reported that when the oil extraction process occurs, 10 percent of the total amount of oil will remain in the protein meal making its characteristics desirable for the fish feed application. It was also reported that the demand for the protein meal currently exceeds the demand for the oil (Pilgeram 2005). Using a software program developed by MSU, Johnson (2005a) calculated the criteria for the production of camelina in Montana and found that Montana could produce 2.5 to 3 million acres camelina annually, based on the current data parameters for soil quality, climatic conditions, rainfall, and growing season.

The following observations are provided related to Montana oilseed crop production that could be used for defense and civilian power generation applications:

- Capacity exists to plant more oilseed crops.
- Opportunities exist for oilseed production as a rotation crop.
- Producers need a higher price for oilseed crops at current production costs or lower production cost crops.
- Producers need a clear understanding of the market demand for biodiesel applications.

Oilseed Crushing and Vegetable Oil Extraction

The state of Montana Three currently has oilseed crushing facilities:

- Montana Specialty Mills (Great Falls)
- Montola Growers Inc. (Culbertson)
- Peaks and Prairies (Malta).

None of these seed crushing facilities are involved with the production of biodiesel at this time. Generally, these facilities produce higher value products rather than biodiesel. However, it was learned during interviews that all of these facilities have an interest in the production of biodiesel from their vegetable oils. Table 17 lists pertinent operating characteristics for two of these three oilseed crushing facilities.

The Montana Specialty Mills seed crushing plant was built in Great Falls approximately 50 years ago. This company markets oilseed and other grain-based products as functional ingredients in food, feed, and industrial end use products. They have temporarily supplied vegetable oil to the University of Idaho for the production of the biodiesel that was used in fleet

vehicles at Yellowstone National Park (Haines and Evanoff 1998). The Montana Specialty Mills facility employs a heated expeller press to extract oil from various seeds including safflower, canola, flax, and sunflower.

This processing plant has the capacity to crush approximately 70,000 lbs of seed per day (Table 17). Roughly one third of the seed weight fed into this crushing plant comes out as vegetable oil, resulting in a capacity of up to 3,040 gal of vegetable oil per day. It was reported that the Montana Specialty Mills crushing plant is currently operating at about their full rate of capacity. Despite this fact, they have expressed interest in obtaining the equipment to produce biodiesel onsite, should it become economically advantageous to do so. This interest was based on the fact that a competitive advantage exists for oilseed crushers to produce biodiesel, given that the cost of oil freight to the biodiesel production site would be avoided.

The Montola Growers Inc. crushing plant was built in Culbertson in 1956, and is the largest oilseed crushing facility in Montana. They currently offer vegetable oil, protein meal, birdseed, and toll-processing services. Uses for their vegetable oil products include cooking oil, infant foods, olive oil blends, spray food coatings, cosmetics, nutritional supplements, floor finishes, paints and biodegradable replacements for petroleum based chemicals. The Montola Growers Inc. facility employs a two-stage oil extraction process, where an expeller press is used to retrieve 65 to 70 percent of the extracted oil and a solvent extraction technique is used subsequently to capture the remaining extractable oil. This two stage extraction technique permits the production of high grade food quality oil.

The various seeds that Montola has crushed include safflower, canola, linola, flax, sunflower, soybean, and crambe. The data in Table 17 show that this processing plant has the capacity to crush approximately 600,000 lbs of seed per day. Roughly 35 to 40 percent of the seed weight fed into this crushing plant comes out as vegetable oil, resulting in a facility capacity of up to 31,260 gal of vegetable oil per day. They have capabilities to refine, bleach, deodorize, and winterize the oils at a rate of up to 600 lbs/hour. They have a seed storage capacity of 1.2 million bushels, oil storage of 2.2 million gal, and meal storage of 8.6 million lb and access to a Burlington/Santa Fe Mainline rail onsite. The Montola Growers Inc. crushing plant currently operates at about 50 to 60 percent of full capacity rate, and has expressed an interest in becoming involved in biodiesel production.

Table 18. Montana oilseed crusher facility characteristics.

Capacity	Montana Specialty Mills	Montola Growers
Plant Location	Great Falls	Culbertson
Type of Extraction	Expeller	Two Stage System Expeller + Solvent
Seed Experience	Safflower, Canola, Flax, and Sunflower	Safflower, Canola, Linola, Flax, Sunflower, Soybean, and Crambe
Seed Processing (lb per day)	70,000	600,000
Oil Production (gal per day)	3,040	27,350 – 31,260
Oil Refining (gal per day)		1,875
Seed Storage (million bushels)	0.5	1.2
Oil Storage (million gal)	0.2	2.2
Meal Storage (million lb)	0.9	8.6
Cost of Oil (USD per gal)	1.54 – 7.68	1.84 – 3.84
Note: Information from Peaks and Prairies was unavailable.		

The Peaks and Prairies Oils Seed Growers Cooperative crusher is located in Malta and currently operates on canola. However, this crusher could operate on different oilseeds with slight preparation/modification. Peaks and Prairies received a Value Added Development Grant in November of 2002 from USDA Rural Development to look at producing oilseed crops for conversion into biodiesel fuel through a partnership with Sustainable Systems, LLC of Missoula. Some of the canola oil they are currently producing is being used to produce chain saw bar oil lubricant. Peaks and Prairies current market focus is bio-lubricant applications as opposed to biodiesel. This strategy is primarily due to their vegetable-based motor oil production expertise and patent protection (Lambert and Johnson 2003).

The following observations relate to oilseed crushing and vegetable oil and biodiesel production in Montana that could be used for power generation applications:

- Capacity currently exists to produce millions of gallons of vegetable oil for biodiesel applications.
- Current crushing and vegetable oil production is used for high value products.
- Existing facilities have interest in biodiesel production opportunities.
- Producers need a clear definition of power generation applications.
- Producers need a clear market demand for biodiesel production.

Biodiesel Production from Montana Vegetable Oil

There are currently no commercial biodiesel producers in the state of Montana. A significant barrier to the investment in these facilities is the lack of a clear market for the biodiesel product. Even though the capital requirements for biodiesel facilities is relatively small, producers are reluctant to invest that capital in the absence of a clear market demand for biodiesel for power generation applications. Sustainable Systems, LLC of Missoula reports that a capital cost rule of thumb for biodiesel plant facilities is roughly $1/gal of the annual production capacity. Sustainable Systems and others claim to have the technology to produce biodiesel from various oilseed crops such as canola and mustard, as well as from waste oils.

Two very important factors for the advancement of biodiesel production are education and awareness initiatives that would help stimulate the growth of biodiesel production and use. Power generator technology manufacturers must more fully embrace biodiesel feedstocks, and also need more effective government mandates to develop renewable fuel portfolios (similar to Executive Order 13123 and the 2 percent fuel mandate in Minnesota).

A variety of Federal and state incentives already exist, primarily for biodiesel production. However, biodiesel use for power generation is a new application and the market risk is still high. There need to be more incentives directed toward reducing the risks related to market entry for biodiesel in power generation applications. The following paragraphs describe a select group of Federal and state incentives.

2002 Farm Bill (Federal)

The Farm Security and Rural Development Act (Farm Bill) of 2002 promotes the development of renewable energy produced in agriculture by encouraging Federal procurement of bio-based products, creating grants and loans for renewable energy projects, and by providing assistance for bioenergy research and development projects (Werner 2003). The appropriation consisted of $405 million in mandatory funding over 5 years (2002 – 2007). Several Sections of the Farm Bill are relevant to power generation:

- *Procurement of bio-based products, Section 9002*, was appropriated in the amount of $6 million ($1 million per year over FY02 – 07) and requires that Federal Agencies purchase bio-based products if they exist with comparable price, performance, and availability characteristics as conventional products.
- *Section 9003, Biorefinery Development Grants*, provides up to 30 percent of a project's cost and is designed to help demonstrate the commercial viability of processes for converting biomass to multiple products.
- *Biodiesel Fuel Education Grants and Loans for Renewable Energy Products, Section 9004*, were appropriated in the amount of $5 million ($1 million per year over FY03 – 07) to educate public and private consumers about the benefits of biodiesel.
- *Grants and Loans for Renewable Energy Products, Section 9005 – Energy Audit and Renewable Energy Resource Assessment Program* require that farmers pay at least 25 percent of audit/assessment costs to evaluate their renewable energy resources and energy efficiency improvement potential. Participating farmers have priority for Sec. 9006.
- *Grants and Loans for Renewable Energy Products, Section 9006 – Renewable Energy System and Energy System Improvements*, are appropriated in the amount of $115 million ($23 million per year over FY03 – 07) to provide farmers grants, loans, and loan guarantees to help purchase renewable energy systems or to make energy efficiency improvements. Grants can cover up to 25 percent of the total project cost, while a loan-grant combination can cover up to 50 percent.
- *Research and Development, Section 9008 – Biomass Research and Development Act*, was appropriated in the amount of $75 million ($14 million per year over FY03 – 07). This program was intended to ensure environmental and economic viability of biomass. Its scope includes the gasification of biomass for use in turbines and fuel cells, lab and field research into feedstock crop growing and handling, as well as conversion of cellulose into sugars.
- *Research and Development, Section 9009 – Carbon Sequestration Research*, provide competitive grants for research on carbon fluxes and exchange of greenhouse gases from agriculture.
- *Research and Development, Section 9010 – Commodity Credit Corporation Bioenergy Program*, was appropriated in the amount of $204 million (up to $150 million per year over FY04 – 06) to compensate

producers of ethanol and biodiesel for commodity purchases to expand production.

- *The Rural Development Title: Value-added Agricultural Product Market Development Program (Section 6401)* is another energy provision contained in the 2002 Farm Bill that allows renewable energy systems to qualify for grants. It was created to stimulate new uses of agricultural products, and the 2002 Farm Bill amended the program to include renewable energy.

Renewable Electricity Production Tax Credit (Federal)

The REPC provides a corporate tax credit of 1.5 cents/kWh, adjusted annually for inflation, for: solar thermal electric, photovoltaics, landfill gas, wind, biomass, geothermal electric, municipal solid waste, cogeneration, refined coal, anaerobic digestion, and small hydroelectric.

Green Power Purchasing Goal (Federal)

Executive Order 13123 is intended to improve the energy management of the Federal government – the nation's single largest consumer of energy. Issued in 1999, this Executive Order requires Federal agencies to increase their use of renewable energy to a percentage determined by the Secretary of Energy. In 2000, the Secretary of Energy directed that Federal agencies obtain the equivalent of 2.5 percent of their electricity from renewable resources by 2005. When the 2.5 percent goal was established in 2000, Federal agencies were obtaining more than 170 GWh from renewables, or about 12 percent of the goal. According to March 2004 data, the Federal government is using approximately 1,067 GWh of renewable energy, or about 77 percent of the revised goal of 1,384 GWh.

Corporate Property Tax Reduction for New/Expanded Generating Facilities (Montana)

Montana generating plants producing 1 megawatt or more by means of an alternative renewable energy source are eligible for a new or expanded industry property tax reduction during the first 9 years of operation, subject to approval by the local government. If so approved, the facility is taxed at 50 percent of its taxable value in the first 5 years after the construction permit is issued. Each year thereafter, the percentage is increased by equal percentages until the full taxable value is attained in the tenth year.

Generation Facility Corporate Tax Exemption (Montana)

New generating facilities built in Montana with a nameplate capacity of less than 1 MW and using an alternative renewable energy source are exempt from property taxes for 5 years after start of operation. “Alternative renewable energy source” means a form of energy or matter, such as solar energy, wind energy, geothermal energy, conversion of biomass, fuel cells that do not require hydrocarbon fuel, small hydroelectric generators producing less than 1 megawatt, or methane from solid waste, that is capable of being converted into forms of energy useful to mankind, including electricity, and the technology necessary to make this conversion.

Alternative Energy Investment Corporate Tax Credit (Montana)

Commercial and net metering alternative energy investments of $5,000 or more are eligible for a tax credit of up to 35 percent against individual or corporate tax on income generated by the investment. The credit may only be taken against net income produced by the eligible equipment or by associated new business activity, that is, it must be a commercial operation.

Residential Alternative Energy System Tax Credit (Montana)

Residential taxpayers who install an energy system using a recognized non-fossil form of energy on their home after 31 December 2001 are eligible for a tax credit equal to the amount of the cost of the system and installation of the system, not to exceed $500.

Renewable Energy Systems Exemption (Montana)

Montana’s property tax exemption for buildings using a recognized non-fossil form of energy generation or low emission wood or biomass combustion devices may be claimed for 10 years after installation of the property. Recognized forms of energy generation include solar, photovoltaics, passive solar, wind, solid waste, decomposition of organic wastes, geothermal, fuel cells that do not require hydrocarbon fuel, small hydropower plants, and wood-burning systems.

NorthWestern Energy—USB Renewable Energy Fund (Montana)

NorthWestern Energy, formerly Montana Power Company, periodically provides funding to its customers for renewable energy projects. As part of

Montana's 1997 restructuring legislation, Montana established its Universal System Benefits (USB) Program. As of 2004, NorthWestern had funded 20 to 25 of more than 30 renewable energy proposals received. Projects included wind and solar projects for residents and businesses and most of the projects included a public education or demonstration component to increase awareness of renewable energy.

BEF—Renewable Energy Grant (Regional)

Using revenues generated from the sales of Green Tags, Bonneville Environmental Foundation (BEF), a not-for-profit organization, provides funding for up to 33 percent of renewable energy projects located in the Pacific Northwest (OR, WA, ID, MT). Any private person, non-profit organization, local or tribal government located in the Pacific Northwest may participate with projects that generate electricity including solar photovoltaics, solar thermal electric, solar hot water, wind, hydro, biomass, and animal waste-to-energy.

Tribal Energy Program Grant (Tribal)

The U.S. Department of Energy (DOE) Office of Energy Efficiency and Renewable Energy's Tribal Energy Program provides financial and technical assistance to tribes for feasibility studies and shares the cost of implementing sustainable renewable energy installations on tribal lands. Funding totaling $2.8 million was allocated to Native American tribes for development of distributed generation for FY02 and $8.3 million was proposed for FY03. The following observations relate to the production of biodiesel from Montana vegetable oil that could be used for power generation applications:

- Capacity currently does not exist to produce biodiesel in Montana.
- Capital costs for biodiesel production facilities are relatively inexpensive, but may be unavailable due to lack of market demand.
- There is a need to clearly define biodiesel market for power generation.
- There is a need to clearly establish the demand for biodiesel for power generation.
- Incentives exist to establish biodiesel production facilities.
- There is a need to establish incentives for use of biodiesel in power generation applications.

- There is a need for demonstration programs for biodiesel applications in power generation to reduce the market risk.

Reforming Biodiesel to Synthesis Gas

Biodiesel fuels can be used directly or they can be converted to a synthesis gas – a high hydrogen containing gas stream – for defense and civilian power generation applications. Synthesis gas is often preferred second only to pure hydrogen for use in many power generation applications, namely in high temperature fuel cells (solid oxide and carbonate) and gas turbines. The selection of a particular reforming technology must be carefully matched to the power generation technology employed since in addition to hydrogen, the remaining components in reformed fuel streams are designed to be either carbon monoxide (CO) or carbon dioxide (CO_2). This is very important in fuel cell applications, for example, since low temperature fuel cells may be poisoned by CO, whereas high temperature fuel cells use CO as fuel. In a prior market survey of reformers for the conversion of vegetable oil or biodiesel into syngas, Adams et al. (2004) concluded that catalytic partial oxidation (CPOX) reforming was the most suitable technology for the production of syngas from canola oil, or other biodiesels, for use with high temperature fuel cell systems.

The application of reforming technologies to biodiesel fuels derived from vegetable oils is new. Only limited laboratory work with reforming technologies and biodiesel fuels was identified and no commercial applications were identified for this study. The cost of reforming systems for biodiesel fuels is high – reflecting the associated risks and the need for more technology development.

Reformer technology applications are not new, however, only their application to biodiesel feedstock. A great potential exists for the application of reformer technologies with biodiesel fuels and the demonstration of those reformer technologies, first on the laboratory scale and then on the small commercial scale. Of particular interest is the development and demonstration of reformer technologies for economically viable Montana oilseed crops. In addition to defense and civilian power generation applications of importance to Montana, this approach is more in line with potential military applications where reformer technologies would be needed for deployed military units who could use indigenous crops and vegetation as fuels for their remote power generation requirements. The following ob-

servations relate to reforming technology application to biodiesel for power generation applications:

- Reformer technologies are well established for power generation applications.
- Reforming of biodiesels is new and not well developed.
- Only limited laboratory work and no commercial applications of reforming technologies with biodiesels are documented.
- There is a need to more fully develop reforming technologies for Montana-based biodiesel products.
- There is a need to conduct laboratory development and demonstration programs for reformer technologies with Montana-based oilseed crops before conducting any field applications of reforming technologies for power generation applications.

Power Generation Applications

Many Montana power generation applications can be characterized as relatively small and remote. The climate and altitude of Montana add special challenges to power generation applications. All of these characteristics are of interest to the DOD for domestic, international, and deployed unit applications.

Small, remote applications are typical of deployed military units that must sustain operations for extended periods of time. The logistic challenges of fuel supply can be overcome or augmented by power generation technology systems that can efficiently function using agricultural or vegetation resources that are indigenous to the deployed units. The application of power generation feedstocks such as biodiesels and technologies such as reformers can be of high value in those military applications.

Chapter 3 of this report identifies and discusses various applications. However, neither these defense related applications nor current civilian applications for biodiesel and reforming technologies in Montana are clearly defined. Nor are there sufficient incentives to help stimulate a market demand for such applications. The following observations relate to power generation applications for biodiesel feedstocks in Montana:

- Applications are not clearly defined.
- Incentive programs exist at both the Federal and state levels to stimulate the production of biodiesel feedstock.

- Different incentive programs are needed at both the Federal and state levels to stimulate the use of biodiesels in power generation applications.
- There is a need demonstration programs for biodiesel use in power generation applications to help mitigate the risk of new product/technology introduction.
- There is a need for more research and laboratory development related to reforming technologies applied to Montana-based oilseed crops in power generation applications.

Summary

This section has reviewed and assessed commercialization characteristics for each of the major process steps in the graphic below. An understanding of the major barriers to commercialization at each of these steps will enable a more dynamic use of Montana-based oilseed biodiesels in defense and civilian power generation applications.

Crop Production / Seed Delivery / Storage
↳ **Seed Crushing / Vegetable Oil Extraction**
↳ **Conversion of Vegetable Oil to Biodiesel**
↳ **Reforming Biodiesel to Synthesis Gas**
↳ ↳ **Power Generation Applications**

Crop production and vegetable oil production capacity already exists. However, the conversion of vegetable oils to their biodiesel corollaries and the application of those biodiesels to defense and civilian power generation applications is limited primarily by the lack of market definition of those applications. Furthermore, the use of reforming technologies with biodiesels to produce of high quality synthesis gas for power generation applications is new and not well developed.

The potential improvement for overall commercialization is high. However, several important commercialization factors must be addressed. Oilseed crop production and vegetable oil production are well established. Incremental improvements can be achieved in each of these process steps, particularly in the development and application of high oil-bearing crops with low production costs. Biodiesel production is lagging due to uncertain market definition and characteristics. While incentives exist to build these

facilities and produce the product, there is still too high a risk for producers due to the absence of market definition. One of the more significant barriers for the use of biodiesels with power generation technologies such as fuel cells and turbines is the need for greater development of reforming technologies for application to biodiesel feedstocks. Table 18 summarizes the commercialization status and potential for economic improvements for production process steps related to the conversion of Montana vegetable oils to biodiesel.

Table 19. Potential for improvement in the overall commercialization.

Process Step	Commercialization Status	Potential for Economic Improvement
Oilseed Crop Production	High	Moderate
Vegetable Oil Production	High	Moderate
Biodiesel Production	Moderate	High
Biodiesel Reforming	Low	High
Market Application	Low	High

The following observations relate to the overall application of Montana-based biodiesel fuels in power generation applications:

- Capacity exists to plant more oilseed crops, but oilseed producers need a clear understanding of the market demand for biodiesel applications.
- Capacity currently exists to produce millions of gallons of vegetable oil for biodiesel applications and existing facilities have interest in biodiesel production opportunities.
- Vegetable oil producers need a clear definition of biodiesel production for power generation applications.
- Capacity currently does not exist to produce biodiesel in Montana; while capital costs for biodiesel production facilities are relatively low, investment capital may be unavailable due to lack of market demand.
- A need exists to clearly define biodiesel market and demand for power generation applications to stimulate the construction of biodiesel production facilities.
- Incentives exist to establish biodiesel production facilities, but different incentives are needed for use of biodiesel in power generation applications. These different incentives could be used for demonstration biodiesel fuels in defense and civilian power generation applications to help reduce market risk.
- Reformer technologies for power generation applications are well established, but reforming of biodiesels is new and not well developed.

- A need exists to more clearly define power generation applications for biodiesels.
- A need exists for demonstration programs for biodiesel use in power generation applications to help mitigate the risk of new product/technology introduction.
- A need exists to conduct laboratory development and demonstration programs for reformer technologies with Montana-based oilseed crops prior to any field applications of reforming technologies for power generation applications.

3 Systems Applications Study

This chapter identifies and evaluates various defense and civilian applications for power generation systems operating on vegetable oil or biodiesel feedstocks derived from Montana oilseed crops. Such applications are of importance to national defense and homeland security criteria. Power generation systems could include boilers, combustion engines, heaters, fuel cells, turbines and micro-turbines, and other systems. Of particular interest in this evaluation is the identification of power generation systems that are applicable to the remote, severe weather, and high altitude conditions characteristic of the state of Montana and also those applications that are relevant to defense and civilian facility and system operations. Defense applications could include both national and international facilities as well as troop deployment operations overseas.

Benefits of Distributed Power Generation

Power generation systems include primary power, auxiliary power, and intermittent power generation. Remote applications for power generation – both civilian and military – can benefit from distributed generation operational concepts. Distributed power generation is small-scale power generation that provides electricity at, or much closer to the remote site, than does central station generation. Central power generation stations benefit from economy of scale cost advantages in power generation, but distributed power generation can, in certain applications, provide benefits that out-weigh these cost advantages:

- greater reliability and few disruptions of the provided electricity
- non-reliance on large scale transmission infrastructure
- high quality of electricity provided
- flexibility to remain autonomous from or interconnected with the existing grid
- less dependence on fuel supply logistics since smaller quantities of fuel can be sourced from various local suppliers
- fuel-flexibility, as smaller power generation technology systems can frequently be adapted for various fuel supplies.

Many of these benefits contribute to the overriding benefit of greater national defense and enhanced homeland security. These power generation characteristics can especially benefit remote communities, farms and ranches, and military installations and deployed military units. These domestic and deployed applications can draw upon local resources – including biodiesel fuels derived from indigenous crops and vegetations – to sustain or augment power generation requirements. Power generation technology systems that are capable of using biodiesel fuels are an important part of the portfolio of available technology options for defense and civilian applications.

The use of biodiesel fuels in power generation applications, however, is very new and not well documented. More experience, although still limited, exists for the use of biodiesel as a transportation fuel and good results have been reported. In power generation (and transportation) applications, biodiesel can be used as a 20 percent blend with 80 percent petroleum diesel. This is referred to as a B20 biodiesel blend. Alternatively, a 100 percent biodiesel product (referred to as a B100) can be used.

Biodiesel Applications

Various applications exist for the use of Montana-based oilseed crops, and their biodiesel corollaries, for defense and civilian power generation applications. Estimated fuel use, based on limited information, ranges from 60 – 75 gal/hr per megawatt generating capacity (BPA). The following list identifies representative, but not all, applications:

- Distributed (Grid Connected or Grid Independent) Generation
    - Base Power for small communities/operations
    - Grid Supplement
- Small Communities
    - Auxiliary power
    - Command Centers
    - Laboratories
    - Lighting
    - Maintenance Facilities
    - Office Buildings
    - Perimeter Fences
    - Water Heating
    - Water Pumping

- Healthcare Facilities
  - Hospitals
  - Clinics
  - Surgery Centers
- Communications
  - Cellular Stations
  - Radio / Television Re-broadcasting
  - Satellite Terminals
- Sensors, Data Acquisition, and Equipment Control
  - Computer operations
  - Security
  - Surveillance.

The following factors are critically important to small remote communities and to defense applications make:

- reliability
- maintainability
- operability
- fuel supply logistics
- fuel flexibility.

One of the most significant issues related to the use of biodiesel – and any alternative fuel – in power generation applications is the reliability of that fuel and the power generating equipment. For example, boilers and diesel gen-sets are traditional systems that are highly reliable. This type of equipment typically lasts 20 years or more. Conversely, fuel cell technologies have been slow to make significant market penetration due in part to factors such as poor reliability, limited availability, high capital cost, and short service lives. Fuel cell stacks generally have a much shorter service life than do conventional power generation equipment. A long service life for a fuel cell stack is generally considered to be about 5 years.

Locations Hosting Biodiesel Applications

Increasingly, biodiesels are being considered for use in power generation applications. For example, Bonneville Power Administration commissioned a study (BPA) related to the use of biodiesel fuels in diesel generators. They had used B20 as part of its transportation fleet, but had no experience with power production. The advantages and disadvantages of

biodiesel for remote portions of their service territory as a distributed energy alternative to transmission and distribution investments were addressed in this study. One particular location of interest is the Olympic Peninsula in Washington State, where distributed generation was being considered as one of a portfolio of actions to defer a potential transmission construction. The following experiences were highlighted in the Bonneville Power Administration study and represent the growing biodiesel experience in power generation applications:

- Scott Air Force Base in Southern Illinois has operated several generators on B20 for monthly testing and then for only 10 minutes at a time. After 12 months of this limited use, the fuel did not perform and they discontinued use of B20 in the generators. Scott AFB continues to use B20 with satisfactory results in the transportation department. They recommend storing biodiesel for no longer than 6 months.
- The USEPA began using B20 at a facility on the Olympic Peninsula in 2004 for heating a laboratory building and for a standby generator. The generator is a 375 kW unit that operates once a month for about 15 minutes, but not under load. No additives are applied to the fuel which is stored in a 10,000-gal underground tank.
- Glacier National Park has operated four units with B20 since 2002. No cold flow additives are included, although the diesel portion is 70 percent of #2 diesel oil and 30 percent of #1 diesel oil. The effect on #1 diesel oil is to improve the flow characteristics in winter. Glacier has experienced no problems with the generators or with the 60 diesel engines in their fleet.
- Mt. Rainier National Park has used B50 in two generators since 2001. The 90 kW units provide continuous power to a remote section of the park during the summer months when that area is open to the public. Each unit runs 24 hours per day for about 2 weeks and then undergoes maintenance while the other unit runs. In addition, the park operates over 50 diesel vehicles, including snowplows, on B20 without any problems.
- Riverside Public Utilities cooperated with the University of California – Riverside on a biodiesel project in 2001. A total of 6 MW from three 2-MW generators was fueled by B100. The generators were tested weekly to help insure availability in the event of a power emergency. The units are no longer fueled with biodiesel.
- Alameda Power and Telecom supplied four emergency generators (1.5 megawatts each) (in 2002) to help keep Alameda a “clean and green

community." Starting in 2004, the utility discontinued the use of biodiesel and substituted a different formulation of diesel with an additive to reduce NOx.

- Blooming Prairie Public Utilities in Minnesota has been using a blend of 2- to 5-percent biodiesel since 2001 to operate a 2 MW and a separate 1.2 MW generator when needed by the Southern Minnesota Municipal Power Agency. Overall, the agency dispatches 190 MW of generator capacity burning B2 to B5 fuels. Typically operations are 300 to 400 hours per year for peaking purposes.
- St. Mary Hospital (2001) in Southern California began using biodiesel in 2001 as the backup to natural gas fuel for boilers and the primary fuel for standby generators. B100 was the only fuel for seven standby generators (totaling 1,765 kW) since it is served from the same 15,000-gal tank serving the boilers. B100 was tested and approved by the air quality management board for a formulation including an additive for NOx reduction.

Biodiesel fuels for power generation (and transportation) applications are reported to run cleaner and require less maintenance than their petroleum-based counterparts. Cold weather issues for biodiesels are just like those for petroleum diesel, in most cases this has not been a problem with 20 percent blends (i.e., B20) since the other 80 percent of the blend is petroleum diesel. B20 has been used without problems in many cold weather areas including upper Wisconsin, upper Minnesota and the Breckenridge Ski area of Colorado. It has also been used in other cold winter areas such as Aspen, Telluride, Spokane, Glacier, and Mt. Rainier. B100 has been used at Yellowstone National Park where vehicles are also equipped with winterization packages (BPA).

B20 may be introduced to power generation applications with little risk. The most likely result would be plugged filters for a period of time as the biodiesel actually cleans out the residues that may have built up on the system. The recommended solution for this situation is to change the filters until the accumulations subside. B100 presents a slightly greater risk. In addition to plugged filters, there is a risk of fuel injector failure. It is recommended that storage tanks be cleaned to remove water and sediment before introducing higher blends like B100. (BPA) Biodiesel chemical and physical characteristics compare favorably to those of petroleum diesel (Table 20), suggesting that direct replacement of petroleum diesel with biodiesel would result in few (or no) operational problems.

Table 20. Composition of various biodiesels, diesels, and alcohols.

Composition	Canola Oil Methyl Ester	Canola Oil Ethyl Ester	Rapeseed Methyl Ester	Rapeseed Ethyl Ester	Sunflower Methyl Ester	Sunflower Ethyl Ester
Hydrogen (wt %)	11.9 – 12.3	12.1	9.0 – 12.4	12.6 – 12.8		
Carbon (wt %)	77.2 – 77.7	77.6	77.7 – 80.7	77.8 – 78.2		
Oxygen (wt %)	10 – 10.8	10.3	9.9 – 10.2	9.2 – 9.4		
Sulfur (ppm)	4 – 90		3 – 300	10 – 320		<200
Density (20 °C, lb/gal)					7.29 – 7.39	7.29
Viscosity (40 °C, cS)	3.8		6.7		4.2 – 5.7	4.9
Viscosity (20 °C, cS)	7		8		15	
Cloud point (°C)	(-3) – (-1)		(-6) – (-2)	(-4)	(-2.8) – 1	
Pour point (°C)	(-4)		(-16) – (-9)	(-18)	(-4)	
Flash point (°C)	162 – 163		84 – 392	406	183	>100
Heating value (BTU/lb)						
Gross (HHV)			17,369 – 17,412	17,498	16,853 – 17,197	16,724 – 17,713
Net (LHV)	17,240		15,993 – 16,251	16,337	16,208 – 16,380	16,552

Table 20. (Cont'd.)

Composition	Soybean Methyl Ester	Soybean Ethyl Ester	Diesel 1	Diesel 2	Ethanol	Methanol
Hydrogen (wt %)	12 – 12.4		12.7 – 13.6	12.7 – 13.1	13.13	12.58
Carbon (wt %)	76.4 – 78.6		85.5 – 86.8	86.0 – 86.9	52.14	37.49
Oxygen (wt %)	9.4 – 11.4		0.0 – 0.96	0.0 – 1.32	34.73	49.93
Sulfur (ppm)	120		35 – 450	230 – 2500		
Density (20 °C, lb/gal)	7.29 – 7.39	7.09	6.84	6.93 – 7.17		
Viscosity (40 °C, cS)	4.0 – 5.7	4.4 – 4.7	1.5 – 1.8	2.0 – 4.3	1.1 – 1.4	
Viscosity (20 °C, cS)				3.5 – 3.8		
Cloud point (°C)	(-5) – 3	1	(-54)	(-18) – (-9)		
Pour point (°C)	(-13.3) – 2	(-4)	(-58)	(-33) – (-18.5)		
Flash point (°C)	160 – 236	174	50	52 – 190	8	10
Heating value (BTU/lb)						
Gross (HHV)	17,111 – 17,154	17,197	19,776	19,475 – 19,690	12,683 – 12,812	9,630 – 9,802
Net (LHV)	15,907 – 17,154	16,251	18,616	18,315 – 18,745		

Source: Adapted from Przybyiski (2000), Peterson et al. (2001), De Winne (2004), Lele (2005), Sharp (1996), Tahir et al. (1982), Megahed et al. (2004), Hawkins and Fuls (1982), Pischinger et al. (1982), and Strayer et al. (1982).

Notes: Insufficient data for crambe, mustard, safflower seeds.

Biodiesels can provide the advantage of being "locally" produced and delivered. This avoids potential disruptions to supply chains to remote facilities and decreases the cost of delivering fuels to remote locations. Depending on delivery cycles, storage capacity and other local infrastructures can be affected. Civilian (and domestic military) applications, such as those in Montana could establish completely new fuel supply chain logistics. For example: local agricultural crops are harvested and converted to biodiesels that are distributed and consumed locally. Advantages to such an approach include stimulating a sustainable local economy and improved homeland security characteristics. Applications for deployed military units could also benefit from enhanced fuel supply logistics. For example: deployed units are able to harvest local and indigenous crops or vegetation for conversion to biodiesel fuels in the field. These biodiesel fuels could be the primary fuel for power generation or could augment traditional fuel supply chain logistics to reduce risks of interruption.

Biodiesel fuels can be used as a primary fuel source or as an augmentation to other fuels, such as petroleum diesel. This provides the added benefit of fuel flexibility in power generation applications. While there is only limited experience with the use of biodiesels in power generation applications, there are indications that these fuels can be direct substitutes in many power generation technology systems. In addition, biodiesels have a significant potential for the conversion to hydrogen-rich synthesis gas through reforming technologies. Hydrogen is of increasing interest in power generation applications including stealth military applications and for other advanced technology applications.

Summary

Chapter 3 identified and discussed various defense and civilian power generation applications and the relevant characteristics of those applications. Of particular interest were the reliability, maintainability, operability, fuel supply logistics, and fuel flexibility of power generation systems.

Power generation technologies for remote communities and installations, and for deployed military units could benefit from the implementation of distributed generation concepts. The findings reported here indicate that, although biodiesel fuels such as those that can be produced from Montana oilseed crops have significant potential in power generation, there is very limited experience in that application. Most of the power generation technology experience has used the biodiesel as a replacement for or augmentation to petroleum diesel in gen-sets.

The following observations related to the application of Montana-based biodiesel fuels in power generation applications:

- Biodiesel fuels hold significant potential in power generation applications.
- Biodiesel fuels have the potential to function as a primary fuel or augmentation to a primary fuel supply.
- Only limited experience has been reported for the use of biodiesels in power generation applications.
- A need exists to conduct laboratory development and demonstration programs with Montana-based oilseed crops in a variety of power generation applications, including gen-sets, turbines and micro-turbines, and fuel cells.
- Laboratory development and demonstration programs are needed for reformer technologies with Montana-based oilseed crops to better understand the technical issues associated with reforming the oils and/or biodiesels to hydrogen for power generation applications.
- Laboratory development and demonstration programs for biodiesel use in power generation applications will help mitigate the risk of new product/technology introduction.
- Laboratory development and demonstration programs for reformer technologies and power generation technologies using Montana-based oilseed crops should be conducted prior to field studies for power generation applications.

4 Conclusions and Recommendations

Conclusions

This study evaluated technical, commercialization and application issues associated with the conversion of harvested biomass — canola and other Montana-based oilseed crops — into a gas stream of sufficient quality to serve as an adequate and sustainable fuel source for use with small power generation technologies, including fuel cells and micro-turbines, in remote defense and civilian power applications. This study concludes that, if efficiently recovered, bio-based materials such as vegetable oils represent an available and renewable source of hydrogen that could serve as an important fuel source for small specialty applications such as remote power generation using micro-turbine, fuel cell, or other technologies, once technological and economic (market-based) conditions for reformation technologies are improved.

The technologies for oilseed harvesting, oil extraction and conversion of the extracted vegetable oil to biodiesel are well-defined, "mature" technologies. Further, reformer technologies for power generation applications are well established, although technologies for reforming vegetable oils or their biodiesel corollaries are not mature. Additionally, power generation applications for biodiesel fuels are still emerging and are not yet well defined (especially those applications that require reforming technologies, such as fuel cells) and will require substantial short-term laboratory research and development.

Crop and vegetable oil production capacity already exists in Montana, and biodiesel fuels such as those that can be produced from Montana oilseed crops have significant potential in small and/or remote power generation applications. However, the conversion of vegetable oils to their biodiesel corollaries and the application of those biodiesel fuels for defense and civilian power generation is currently limited—primarily by the lack of market definition of those applications.

Capital costs for reforming technologies dominate the overall economics of converting vegetable oils to a hydrogen rich synthesis gas (Table 16, p 42). While incentives to build production facilities exist, the risk is still too high for producers to "jump into" the market. There is great potential to im-

prove the overall commercialization once those important commercialization factors (biodiesel production and reforming, and market application) are addressed (Table 19, p 58). There is also great potential for improvement in economic performance of reforming technologies due mostly to the early stage of technology maturity (Table 16, p 42).

Small, remote power generation systems operating with agriculturally derived fuels can take advantage of numerous dual-use opportunities; biodiesel can fuel both fuel-cell and traditional diesel applications. Remote communities, military installations, and deployed military units could benefit from implementing distributed power generation technologies.

Recommendations

To advance the use of Montana-based vegetable oils and their biodiesel corollaries in small and/or remote power generation applications, subsequent research should focus on several technical and economic (market-related) areas:

1. Laboratory development and demonstration programs should focus on resolving technological issues associated with reforming vegetable oil and biodiesel to hydrogen for power generation applications. This would be most effectively achieved by placing a short-term research emphasis on reformer technology investigations rather than on field demonstrations of various reformer technologies suitable for application with Montana-based agricultural crops
2. Investigations should consider a range of defense and civilian power generation technology alternatives, e.g., fuel cell, micro-turbine, combustion engines, etc., that could use either vegetable oil, biodiesel or the syngas produced from the reformation of biodiesel.
3. Economic research should clearly define and demonstrate how a biodiesel market and demand for power generation applications can combine to stimulate the construction of biodiesel production facilities. This may be achieved by creating incentives to stimulate the use of biodiesel fuels in power generation applications.

While potential commercial and military applications for small, remote power generation systems do exist, there is a need to demonstrate these technologies. This study recommends that such demonstrations should be conducted at defense and other government facilities, and in private sector facilities to better define market applications and characteristics, and to stimulate vegetable oil and biodiesel production from Montana agriculture for those power generation applications.

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14. ABSTRACT

This study evaluated the use of Montana-based oilseed crops (canola oil) for power generation in defense and civilian fuel-cell applications. Three major fuel production operations were considered: (1) recovery of oil from the harvested vegetable crop, (2) conversion of the vegetable oil into its biodiesel corollary, and (3) reforming the biodiesel into a synthesis gas. The study explored areas for potential improvements in the cost or technical performance in these major operations. Various commercialization pathways for agriculturally derived fuels were evaluated, with an emphasis on dual use opportunities. This work identified potential commercial and military applications for small, remote power generation systems, including fuel cells, which operate using those agriculturally derived fuels. This report documents barriers to commercialization that must be overcome, potential resolutions to those barriers, and stimuli for commercialization that can effectively advance the interests of key Department of Defense and Montana stakeholders in using Montana-based vegetable oil crops for remote power generation.

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